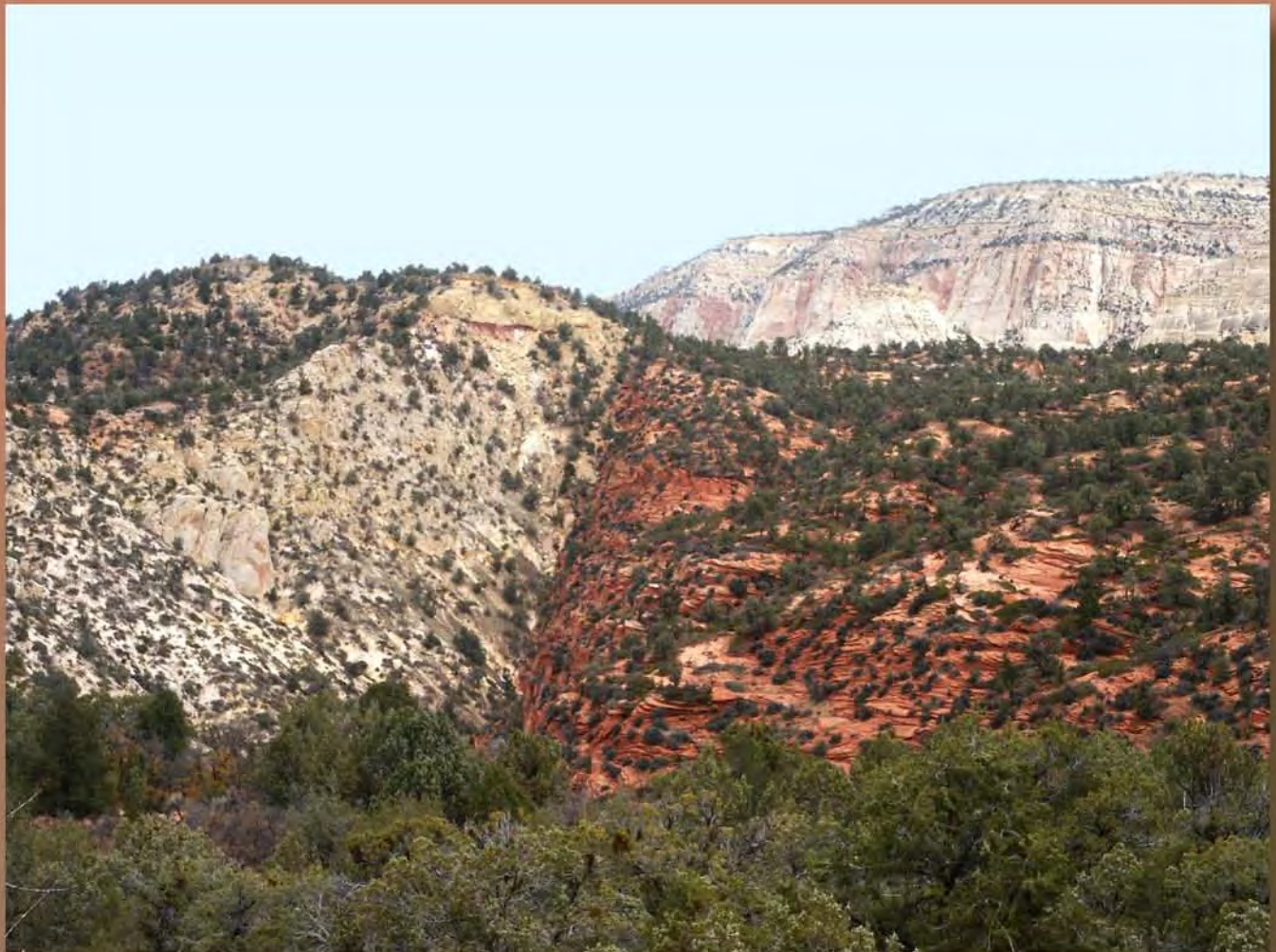


*Paleoseismology of Utah, Volume 16*

# PALEOSEISMIC RECONNAISSANCE OF THE SEVIER FAULT, KANE AND GARFIELD COUNTIES, UTAH

*by*

*William R. Lund, Tyler R. Knudsen, and Garrett S. Vice*



**SPECIAL STUDY 122**  
**UTAH GEOLOGICAL SURVEY**  
*a division of*  
**Utah Department of Natural Resources**  
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**Cover Photo:** *Sevier fault in the Navajo Sandstone near Mt. Carmel Junction, Utah. View is to the northeast.*

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## FOREWORD

This Utah Geological Survey Special Study, *Paleoseismic Reconnaissance of the Sevier Fault, Kane and Garfield Counties, Utah*, is the sixteenth report in the Paleoseismology of Utah series. This series makes the results of paleoseismic investigations in Utah available to geoscientists, engineers, planners, public officials, and the general public. These studies provide critical information regarding paleoearthquake parameters such as earthquake timing, recurrence, displacement, slip rate, and fault geometry, which can be used to characterize potential seismic sources and evaluate the long-term seismic hazard presented by Utah's Quaternary faults.

This report presents the results of a study partially funded through the National Earthquake Hazards Reduction Program to characterize the relative level of activity of the Sevier fault in southwestern Utah. The Sevier/Toroweap fault trends generally north-south through southwestern Utah and northern Arizona; by convention the fault is known as the Sevier fault in Utah and the Toroweap fault in Arizona. Approximately 108 kilometers of the 250-kilometer-long fault are in Utah. This study focused on the Utah portion of the fault and involved aerial-photograph analysis, field reconnaissance, detailed mapping of selected areas along the fault, and new major- and trace-element geochemical analyses and  $^{40}\text{Ar}/^{39}\text{Ar}$  radiometric ages for volcanic rocks displaced by the fault. Determining paleoseismic parameters for the Sevier fault is important because they help the Utah Geological Survey assess the level of seismic hazard presented by the fault to southwestern Utah, and assist the U.S. Geological Survey in updating the Quaternary Fault and Fold Database of the United States and evaluating the Sevier fault's significance to the National Seismic Hazard Maps.

Paleoseismic results of this study include estimates of geologic (average vertical) slip rates and surface-faulting recurrence intervals at two critical locations along the fault in Utah, and identification of two new possible seismogenic segment boundaries along the Utah portion of the fault.

William R. Lund, Editor  
Paleoseismology of Utah Series



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# PALEOSEISMIC RECONNAISSANCE OF THE SEVIER FAULT, KANE AND GARFIELD COUNTIES, UTAH

by

*William R. Lund, Tyler R. Knudsen, and Garrett S. Vice*

## ABSTRACT

The Utah Geological Survey conducted a paleoseismic reconnaissance of the Sevier fault in southwestern Utah to develop information on earthquake timing and recurrence, and fault displacement and vertical slip rate. The reconnaissance included a literature review, aerial-photograph interpretation, field reconnaissance, and sampling of displaced Quaternary volcanic rocks for  $^{40}\text{Ar}/^{39}\text{Ar}$  radiometric dating and geochemical analysis. Results of the reconnaissance showed no fault scarps on unconsolidated deposits along the main trace of the Sevier fault in Utah, although scarps are reported on Pleistocene deposits where the fault extends into Arizona, and numerous scarps and folds deform Pleistocene alluvium in the fault hanging wall near Panguitch. The fault displaces Quaternary volcanic rocks at Black Mountain and Red Canyon in Kane and Garfield Counties, respectively.

Geologic relations at Black Mountain are complex, poorly exposed, and complicated by pre-existing topography and landslides. Previous vertical-slip-rate estimates calculated there range from 0.0180 to 0.40 mm/yr depending on the amount of displacement attributed to surface faulting. We could not reliably determine surface-faulting displacement at Black Mountain, and therefore calculated a middle Miocene to present vertical slip rate for the fault using a first-order fault age estimate of 12-15 Ma, and an estimated total displacement of 472 to 869 m from geologic cross sections. Assuming an average 2.0 m displacement per surface-faulting earthquake, our long-term vertical-slip-rate estimate at Black Mountain of 0.03-0.07 mm/yr yields a mean surface-faulting recurrence interval of 40 kyr. The low slip rate and corresponding long surface-faulting recurrence are consistent with the absence of scarps on unconsolidated deposits at Black Mountain.

New  $^{40}\text{Ar}/^{39}\text{Ar}$  radiometric ages show that volcanic flows of two different ages are present at Red Canyon: a  $0.51 \pm 0.02$  Ma late Pleistocene flow and a  $4.96 \pm 0.03$  Ma early Pliocene flow. New geochemical analyses demonstrate that both flows are correlative across the Sevier fault. We identified a previously unrecognized source for the younger volcanic flow on the fault hanging wall, indicating that the difference in elevation of the flow across the fault is due to surface faulting and not cascading across a pre-existing fault escarpment from a source on the footwall. The older flow likely also has a western source. The new radiometric ages and displacement estimates of 192-225 m for the younger flow and 237-344 m for the older flow yield late Pleistocene to present and early Pliocene to present vertical-slip-rate esti-

mates of 0.38-0.44 mm/yr, and 0.05-0.07 mm/yr, respectively. Seismic reflection data show about 900 m of displacement in basement rocks at Red Canyon. Using the first-order age estimate for the Sevier fault of 12-15 Ma, we calculated a middle Miocene to present vertical-slip-rate estimate of 0.06-0.08 mm/yr. Using the new vertical slip rates and an average displacement of 2.0 m for surface-faulting earthquakes at Red Canyon, we calculated average surface-faulting-recurrence-interval estimates for the late Pleistocene of 4.9 kyr, an early Pliocene to present interval of 33 kyr, and middle Miocene to present interval of 29 kyr. Given the comparatively high vertical slip rate and short average recurrence interval during the late Pleistocene at Red Canyon, the absence of fault scarps on unconsolidated deposits at that location is puzzling.

Deformation of unconsolidated basin-fill deposits in the Sevier fault hanging wall includes a zone of faults and folds that extend from the hills directly south of Panguitch north-eastward across the Sevier River to east of Panguitch, and a short north-south-trending graben on the east side of the Sevier River north of Panguitch. The faults displace deposits ranging in age from late Pleistocene to late Tertiary, and the associated scarps vary in height from less than a meter to about 25 m. Trenching these scarps would reveal if they formed in response to coseismic surface faulting or aseismic folding. However, what relation surface-faulting earthquakes in the fault hanging wall may have to the timing of surface-faulting earthquakes on the main Sevier fault will remain unresolved due to the absence of scarps and therefore trenching sites on the main trace of the Sevier fault.

Like other large normal-slip faults in the Basin and Range Province, we suspect that the 250-km-long Sevier fault consists of shorter seismogenic segments, and that each segment has a unique rupture history. In addition to the 2.5-km-wide left step-over in the Sevier fault near Clay Flat previously recognized as a possible segment boundary, we propose two other possible segment boundaries in Utah. Coincident geometric and geomorphic anomalies, differences in stratigraphic displacement, and changes in seismic activity at Hillsdale Canyon and near Alton are characteristic of seismogenic segment boundaries; however, our segmentation model remains speculative until independent rupture histories on the proposed segments can be demonstrated.

## INTRODUCTION

The Utah Geological Survey (UGS) conducted a paleoseismic reconnaissance of the Sevier fault in southwestern

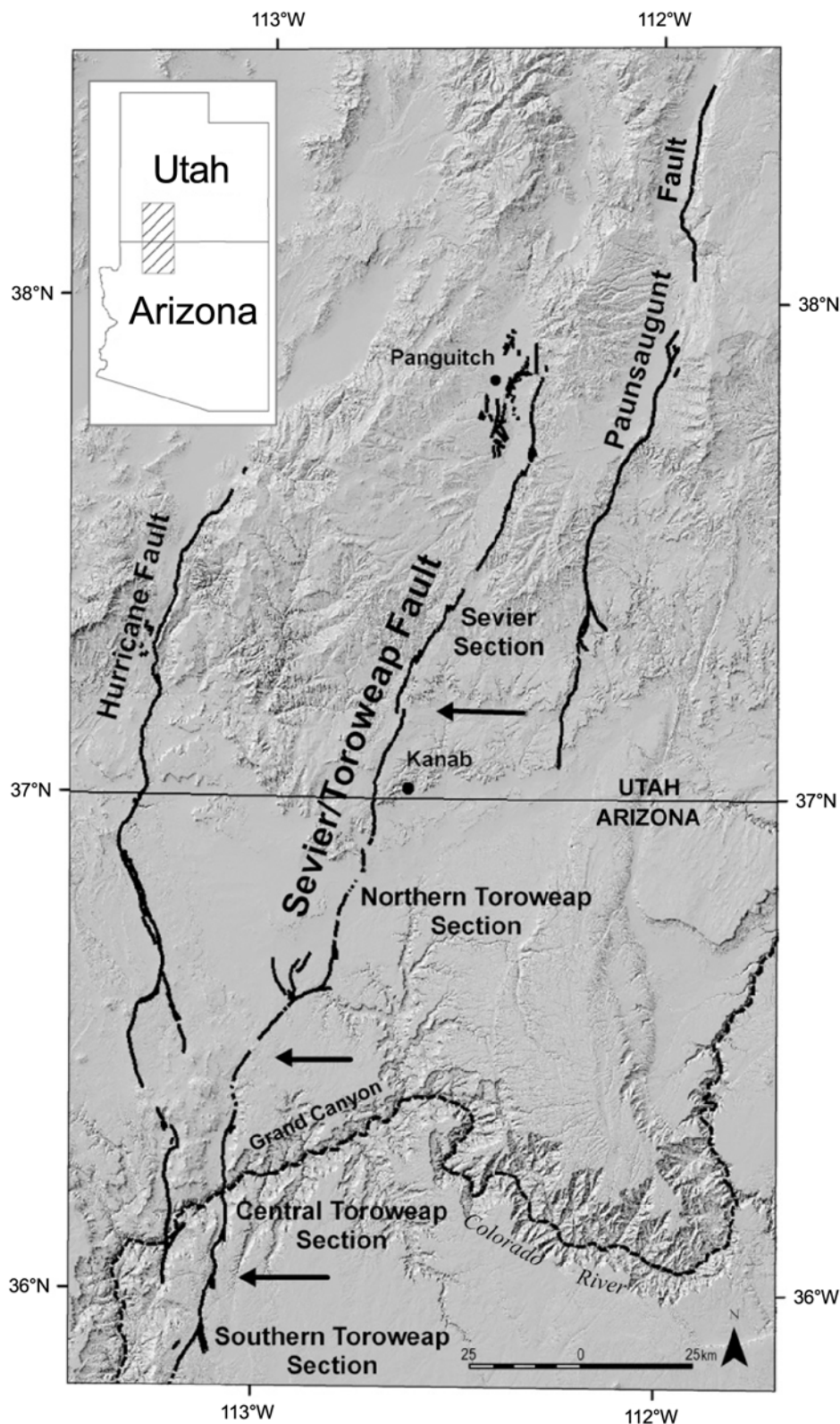
Utah to develop new information on earthquake timing, recurrence, displacement, and average vertical slip rate. Determining all or some of these paleoseismic parameters will help the UGS assess the level of seismic hazard presented by the Sevier fault to southwestern Utah, and assist the U.S. Geological Survey (USGS) in updating its Quaternary fault database and evaluating the fault's significance to the USGS National Seismic Hazard Maps.

Our investigation included a literature review, aerial-photograph interpretation (chiefly 1:40,000-scale with 1:20,000-scale stereoscopic photos of select areas), field verification of fault features and geologic units, and sampling of Quaternary volcanic flows for  $^{40}\text{Ar}/^{39}\text{Ar}$  radiometric dating and geochemical analysis.

## OVERVIEW

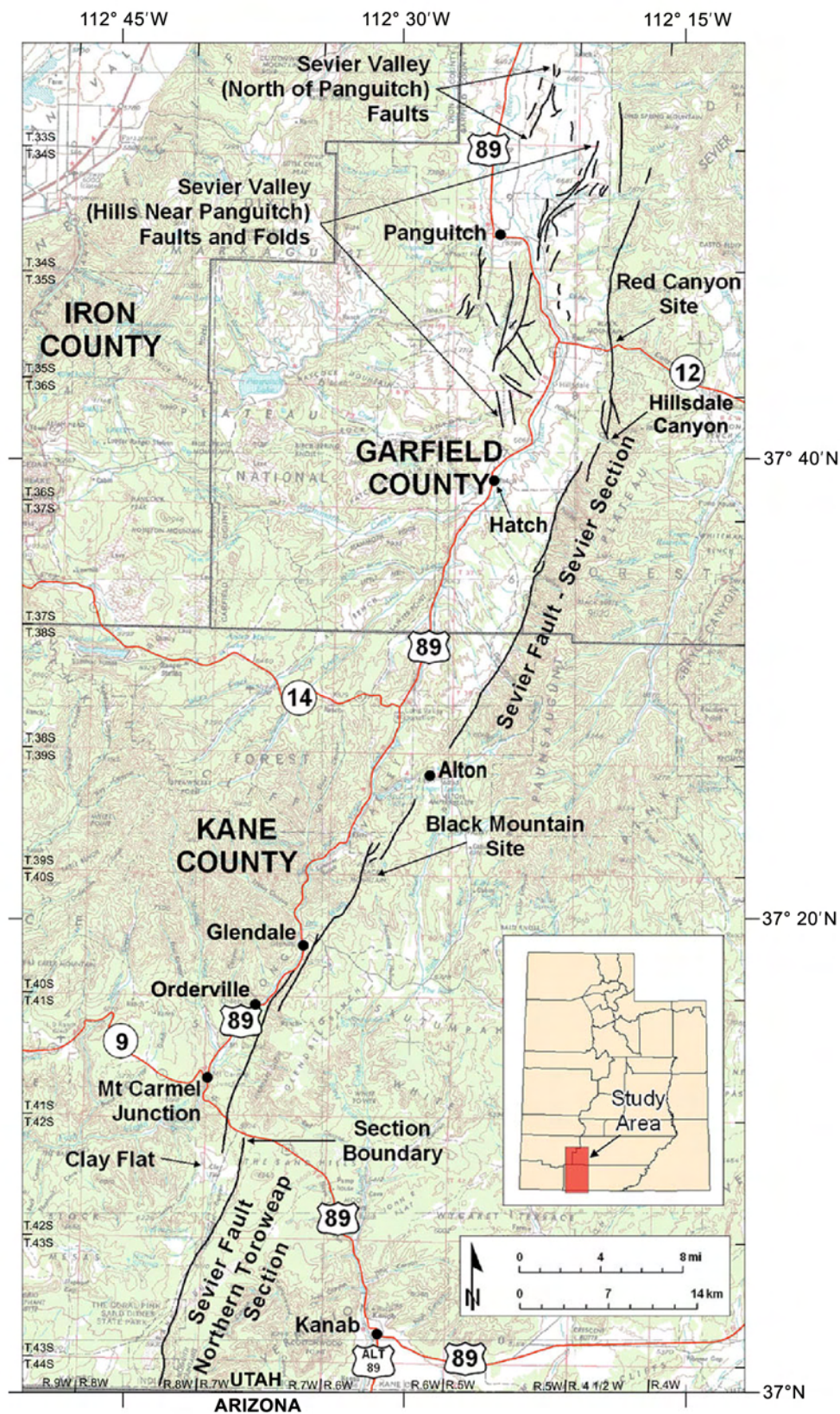
As defined by Black and others (2003), the Sevier fault is the Utah portion of the longer Sevier/Toroweap fault, a left-lateral, oblique-slip fault that extends from south of the Colorado River in Arizona to north of Panguitch, Utah (figure 1). The Sevier/Toroweap fault is one of three major sub-parallel, generally north-trending faults (along with the Hurricane fault to the west and Paunsaugunt fault to the east) in northwestern Arizona and southwestern Utah that define the transition between the Basin and Range Province to the west and the Colorado Plateau to the east. Although a continuous structure that is almost 250 km long (Pearthree, 1998; Black and others, 2003), by convention the Sevier/Toroweap fault is named the Toroweap fault in Arizona and the Sevier fault in Utah. We follow that convention in this report.

Displacement along the Sevier/Toroweap fault is variable, but generally increases to the north. In Arizona, Pearthree (1998) reported as much as 300 m of Cenozoic displacement near the Grand Canyon, but only about 100 m of displacement across the Kanab Plateau to the north near the Utah-Arizona border. In Utah, Anderson and Christenson (1989) reported displacements of 450 m near Mt. Carmel Junction and 900 m at Red Canyon (figure 2). Schiefelbein



**Figure 1.** The Sevier/Toroweap fault and other major faults in the Basin and Range – Colorado Plateau transition zone; arrows indicate fault section boundaries after Pearthree (1998) and Black and others (2003).





**Figure 2.** The Sevier fault in Utah showing Clay Flat, Black Mountain, Alton, Hillsdale Canyon, Red Canyon, and hanging-wall faults near Panguitch; fault section boundaries after Black and others (2003). Base maps: U.S. Geological Survey Kanab and Panguitch 30 x 60 minute topographic quadrangles.



(2002) studied a 12-km-long section of the Sevier fault between Orderville, Utah, and Black Mountain, and reported a stratigraphic separation across the fault in her study area of 472 to 869 m. Along its length, the Sevier/Toroweap fault typically forms a west-facing bedrock escarpment, the height and steepness of which depend on the resistance of the bedrock units displaced at the ground surface. Near the Utah-Arizona border and extending to Glendale, Utah (figure 2), the Sevier fault displaces the Navajo Sandstone and other well-indurated Triassic and Jurassic strata, and the resulting bedrock escarpment is typically tens to hundreds of meters high and commonly forms a near-vertical cliff (figure 3). North of Glendale, the Sevier fault is exposed in less resistant Cretaceous and Cenozoic rock units, and the escarpment is lower and less precipitous.

At a few locations along the fault, more-resistant rock in the hanging wall is in contact with less-resistant rock in the footwall, and erosion has inverted the topography and produced obsequent fault-line scarps. Obsequent fault-line scarps are particularly well developed near Pipe Springs National Monument in Arizona where the more resistant Kayenta Formation and Navajo Sandstone maintain the hanging wall at a high elevation compared to the less resistant Moenkopi Formation in the footwall. A similar relation exists near Alton, Utah (figure 2), where an obsequent fault-line scarp extends from a few kilometers southwest to several kilometers northwest of town. There, the moderately resistant Eocene Claron Formation in the hanging wall forms the highest part of a ridge, whereas less resistant Cretaceous rock in the footwall is at lower elevations (figure 4).

Pearthree (1998) divided the Toroweap fault into three sections in Arizona, the northernmost of which (Northern Toroweap section) he arbitrarily terminated at the Utah-Arizona border. Sargent and Philpott (1987) showed uninterrupted faulting continuing northward across the border into Utah for an additional 20 km before the fault makes a 2.5-km left step at Clay Flat about 6.5 km south of Mt. Carmel Junction (figure 2). Based on the presence of the left step and an apparent pull-apart basin (Clay Flat) formed there by left oblique slip on the fault (Anderson and Christenson, 1989), Black and others (2003) subdivided the Sevier fault in Utah into two sections: (1) an extension of Pearthree's (1998) Northern Toroweap Section continuing from the Utah/Arizona border north to Clay Flat, and (2) the Sevier section extending for an additional 88 km (straight line) from Clay Flat to north of Panguitch (figure 2). At its northern end, the Sevier fault terminates within the thick Miocene Marysville volcanic field. An aerial-photograph study of this area by Anderson and Christenson (1989) showed that scarps are absent in the volcanic rocks and that possible fault traces are expressed only as aligned drainages in bedrock.

In addition to the main Sevier fault, Anderson and Christenson (1989) identified two other groups of faults/folds near Panguitch in the Sevier fault hanging wall. They are the "Sevier Valley (Hills Near Panguitch) faults and folds" and "Sevier Valley (North of Panguitch) faults" (figure 2) (Hecker, 1993; Black and others, 2003). Anderson and Christenson (1989) believed both groups of hanging-wall faults/folds are genetically related to the main Sevier fault. This study includes both sections of the main Sevier fault and both



**Figure 3.** Sevier fault in the Navajo Sandstone (sharp color contrast in the foreground) near Mount Carmel Junction, Utah; the steep Navajo Sandstone escarpment in the distance is also formed by the Sevier fault. View is to the northeast.



**Figure 4.** Oblique fault-line scarp formed on the Sevier fault northwest of Alton, Utah. Resistant Eocene Claron Formation (red) in hanging wall forms a ridge whereas less resistant Cretaceous sedimentary rock in the footwall crops out in the valley. View is to the northeast.

groups of faults/folds near Panguitch. The scope of work for this reconnaissance did not include investigating the Sevier Valley fault (Hecker, 1993; Black and others, 2003), which lies near Marysville in the southern Sevier Valley approximately 22 km north of the northern terminus of the Sevier fault.

## PREVIOUS WORK

The Sevier fault has long been recognized as a major block-bounding structural discontinuity in southwestern Utah that displaces near-horizontal Mesozoic and Cenozoic strata and Cenozoic volcanic rocks down-to-the-west (Gilbert, 1875; Dutton, 1880). However, recognition that the Sevier fault is an active fault and a potential source of damaging earthquakes is more recent.

Gregory (1951) discussed the Sevier fault and stated that earthquakes recorded at Tropic and Panguitch (east and west of the Sevier fault, respectively) in 1902, 1924, 1930, and 1931 may have had their foci on faults in the region, without indicating which fault or faults might have been involved. Cashion (1961, 1967) mapped part of the Sevier fault in the Glendale-Orderville area and reported that mafic volcanic rocks at Black Mountain in northern Kane County are displaced across the fault. He also mentioned the 1902 to 1931 Glendale earthquakes, and suggested that the Sevier fault may still be active.

Anderson and Rowley (1987) mapped the Panguitch NW quadrangle and showed faults cutting late Pleistocene

and Holocene deposits east of the Sevier River north of Panguitch (the Sevier Valley [North of Panguitch] faults of Hecker (1993) and Black and others [2003]). Anderson and Rowley (1987) stated that those faults provide evidence of significant Quaternary and possible ongoing Holocene tectonic activity. Doelling and Davis (1989) discussed earthquake hazards in Kane County, and ascribed 14 earthquakes between 1924 and 1927 having modified Mercalli intensities as high as III in the vicinity of Orderville, Utah, to movement on the Sevier fault. They also noted that the fault displaces Quaternary volcanic rocks at Black Mountain.

Anderson and Christenson (1989) discussed the Sevier fault and associated faults and folds near Panguitch. They were the first to specifically address Quaternary tectonic features in southwestern Utah, and to evaluate their potential for generating large surface-faulting earthquakes. Covering an area of several thousand square miles, the Anderson and Christenson (1989) report is a broad reconnaissance study that includes numerous Quaternary tectonic and volcanic features in addition to the Sevier fault. The report documented displaced Quaternary volcanic rocks at two locations along the Sevier fault, Black Mountain in Kane County and Red Canyon in Garfield County; identified Clay Flat as a possible pull-apart basin suggestive of possible late Pleistocene oblique-slip fault movement; documented likely non-tectonic displacement on the fault along a 2 km section of an oblique fault-line scarp near Alton, Utah; and discussed the faults and folds in the Sevier fault hanging wall near Panguitch.



Moore and Staub (1995) and Kurlich and Anderson (1997) prepared geologic maps of the Panguitch and Hatch USGS 7.5-minute quadrangles, respectively. Both maps show faults thought to be genetically associated with the Sevier fault cutting Quaternary-age deposits.

Harbor (1998) studied changes in the morphology of the Sevier River where it crosses the fault-and-fold zone in the Sevier fault hanging wall east and south of Panguitch, and concluded that the area is one of active tectonic uplift. Davis (1999) and Reber and others (2001) studied structural details of the Sevier fault. Both reported evidence of Quaternary movement, and based on historical seismicity Davis (1999) suggested that the Sevier fault is active. Schiefelbein (2002) addressed fault segmentation, fault linkage, and hazards along a 12-km-long section of the Sevier fault between Orderville and Black Mountain in Kane County. In addition to producing a detailed (1:12,000 scale) geologic map of her study area, she provided new information on the age of the displaced volcanic rocks at Black Mountain, and new estimates from cross sections of total displacement across the fault in her study area.

Geologists also recognize that the Toroweap fault in Arizona is potentially active. Detailed geologic mapping and soils and geomorphologic analyses by Jackson (1990) indicated Holocene rupture along about 50 km of the Central Toroweap section (figure 1) centered on the Colorado River. Pearthree (1998) summarized information regarding Quaternary fault activity on the Southern, Central, and Northern Toroweap sections of the Toroweap fault through mid-1998. Fenton and others (2001a, 2001b) used cosmogenic isotope ages on displaced basalt flows to calculate vertical slip rates for the Central Toroweap section at Grand Canyon.

Hecker (1993) and Black and others (2003) summarized existing paleoseismic information available for the Sevier/Toroweap fault zone and nearby hanging-wall faults in Utah.

## SEISMICITY

No historical surface-faulting earthquakes have occurred on the Sevier/Toroweap fault. To investigate contemporary Sevier fault seismicity, we plotted historical earthquake epicenters from the University of Utah Seismograph Stations catalog for the period 1962 to 2006 (instrumental data – prior to 1962 the catalog consists chiefly of felt reports) that are coincident with the fault trace in Utah (figure 5). The events within this time period were magnitude 3 or smaller, and the resulting earthquake pattern shows that seismicity is significantly more abundant north of the obsequent fault-line scarp (gap in Quaternary faulting) near Alton. North of the “Alton gap,” earthquake epicenters are present on both the fault footwall and hanging wall, and are particularly abundant near Panguitch where hanging-wall scarps displace Quaternary alluvial deposits (Sevier Valley [Hills Near Panguitch] faults and folds” and the “Sevier Valley [North of Panguitch] faults” [figures 2 and 5]). One small cluster of epicenters is centered directly on the Sevier fault at the mouth of Red Canyon.

South from the Alton gap to Clay Flat, earthquake epicenters are less abundant and are largely restricted to the fault hanging wall. Beginning near Clay Flat and extending

south into Arizona, epicenters on the Northern Toroweap section become more abundant in the hanging wall, but remain largely absent from the footwall (figure 5).

## PALEOSEISMIC RECONNAISSANCE

This paleoseismic reconnaissance includes the main trace of the Sevier fault from the Utah-Arizona border to the fault's terminus north of Panguitch, Utah (figure 2). The end-to-end length of the Sevier fault in Utah is approximately 108 km, and incorporates the 20-km extension of Pearthree's (1998) Northern Toroweap section in Utah, and the 88-km-long Sevier section (Black and others, 2003) north of Clay Flat. This reconnaissance also includes the two groups of faults and folds in the Sevier fault hanging wall near Panguitch: the Sevier Valley (Hills Near Panguitch) faults and folds, and the Sevier Valley (North of Panguitch) faults (figure 2).

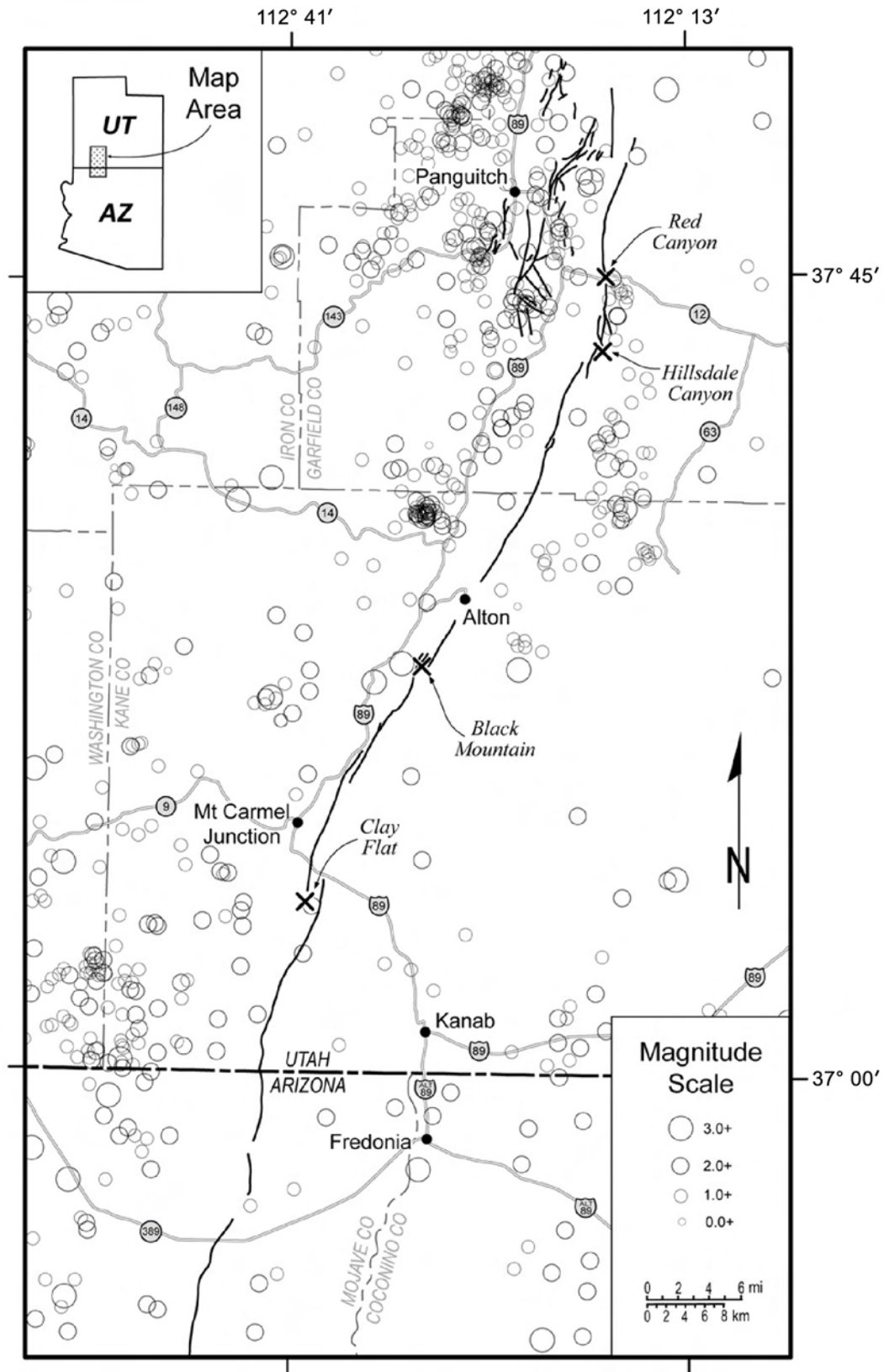
### Sevier Fault Main Trace

#### Northern Toroweap Section

Pearthree (1998) defined the Northern Toroweap section as extending from the northern end of Toroweap Valley in Arizona to the Utah-Arizona border (figure 1), where he arbitrarily terminated the section because he was only compiling Quaternary fault data for Arizona. Sargent and Philpott (1987) mapped the Kanab 1:62,500-scale quadrangle in Kane County, Utah, and Mohave and Coconino Counties, Arizona, and demonstrated that the Northern Toroweap section extends as a single uninterrupted fault section from Arizona into Utah for an additional 20 km to Clay Flat about 6.5 km south of Mt. Carmel Junction (figures 1 and 2). Doelling and Davis (1989) compiled a geologic map of Kane County at 1:100,000 scale and included the Utah portion of the Northern Toroweap section on their map.

Where exposed in bedrock, faults comprising the Northern Toroweap section in Utah define a zone as much as a kilometer wide of overlapping and anastomosing fault strands. Sargent and Philpott (1987) identified several locations where Holocene alluvial, eolian, and mixed alluvial/eolian deposits bury parts of the Northern Toroweap section, and one location where the section is overlain by Pleistocene gravel. They do not show faulting cutting those deposits. In contrast, Doelling and Davis (1989) show a strand of the Northern Toroweap section cutting a Holocene eolian dune deposit in section 24, T. 43 S., R. 8 W., Salt Lake Base Line (SLBL), and displacing the previously mentioned Pleistocene gravel deposit in section 17, T. 42 S., R. 7 W., SLBL. Our aerial-photograph interpretation and field reconnaissance did not verify the displaced deposits shown on the Doelling and Davis (1989) map, nor identify displaced Quaternary deposits elsewhere on the Northern Toroweap section in Utah.

Pearthree (1998) reported that a fault scarp formed on alluvium on the Northern Toroweap section near Pipe Springs National Monument in Arizona is about 3.5 m high and has a maximum slope angle of 7.5°, which suggests a late Pleistocene age. However, our aerial-photograph interpretation and field reconnaissance showed that scarps formed



**Figure 5.** Earthquake epicenters along the Sevier fault in Utah (Relu Burlacu, University of Utah Seismograph Stations, written communication, 2007).



on unconsolidated deposits are absent along the Northern Toroweap section in Utah.

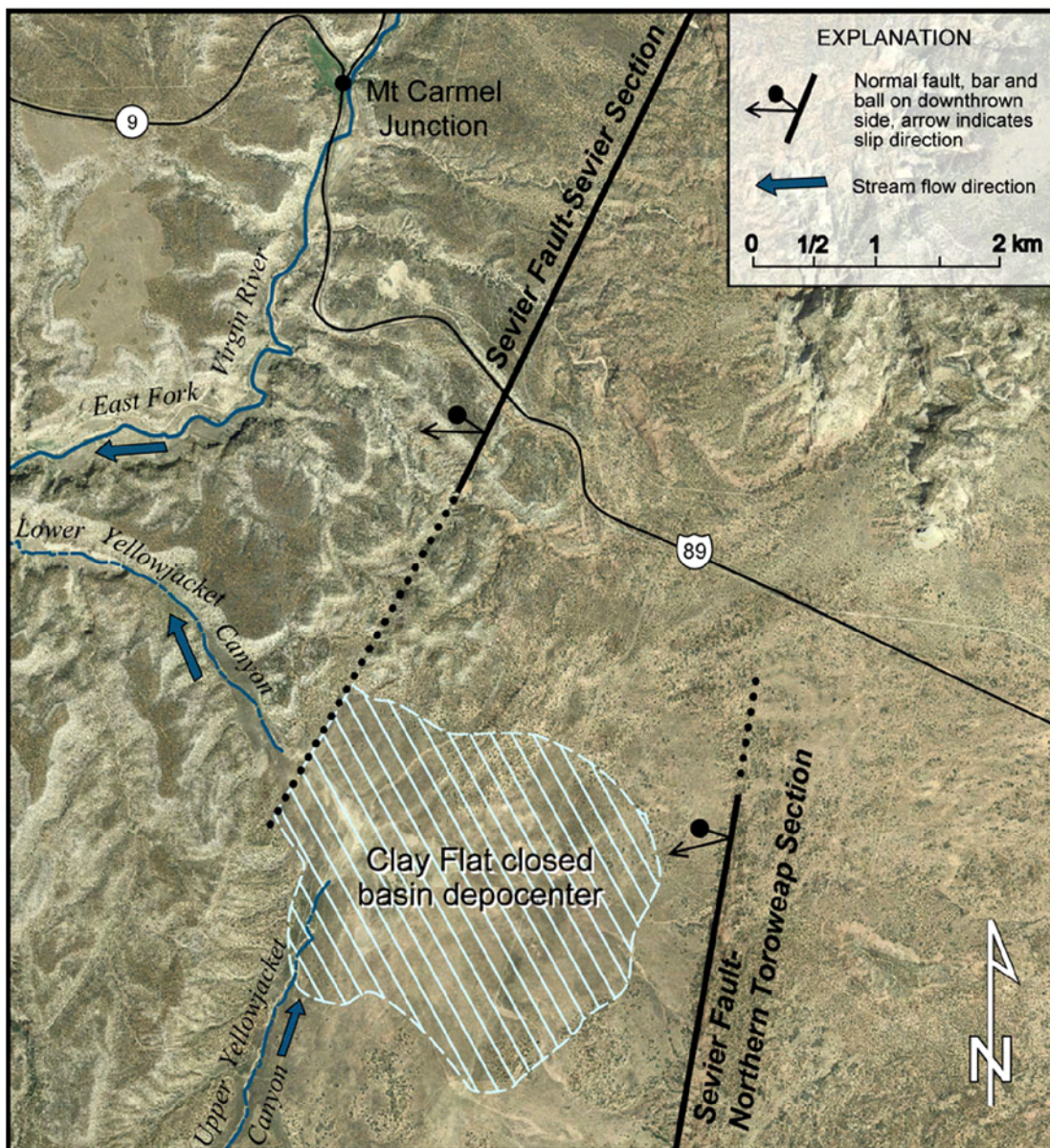
### Clay Flat

Clay Flat forms a small (1 km<sup>2</sup>) closed basin where the Sevier fault makes a left en echelon step between the Northern Toroweap section on the east and the Sevier section on the west (figures 2 and 6). Clay Flat receives sediment chiefly from the south via the Yellowjacket and Sethys Canyon drainages, and to a lesser extent from small, unnamed drainages to the east and north. The combined drainage area for Clay Flat is about 70 km<sup>2</sup> (Anderson and Christenson, 1989). The Clay Flat closed basin is superimposed upon the much larger Yellowjacket drainage basin and divides that basin into disconnected upper and lower reaches. The upper reach drains into Clay Flat, whereas the lower

reach is tributary to the East Fork of the Virgin River (figure 6). Headward erosion on the lower reach is presently within about 350 m of Clay Flat, and the drainage divide between the basin and the stream channel is only a few meters high, indicating geologically imminent stream capture, which will reconnect the upper and lower Yellowjacket drainages.

Anderson and Christenson (1989) documented left-lateral oblique slip on the Northern Toroweap section south of Clay Flat, and noted that left-lateral slip at a left en echelon step in the fault trace would produce concentrated dilation and form a pull-apart basin at the step-over between the fault sections. They further speculated that maintaining a small sediment depocenter in the much larger Yellowjacket drainage basin would require active late Pleistocene subsidence.

Our aerial-photograph interpretation and field reconnaissance confirmed the observations regarding Clay Flat as presented by Anderson and Christenson (1989), but did not



**Figure 6.** Clay Flat closed-basin depocenter formed in the Yellowjacket drainage basin at a 2.5-km left step in the trace of the Sevier fault about 20 km north of the Utah-Arizona border. Sevier fault dips west, arrows on fault traces show left-lateral, oblique slip direction (after Anderson and Christenson, 1989). See figure 2 for the location of Clay Flat.



identify relations between faults and sedimentary deposits in or near the basin that would allow Anderson and Christenson's (1989) hypothesis regarding Pleistocene subsidence to be tested. Undeformed Holocene surficial deposits overlie the Sevier fault in the vicinity of Clay Flat indicating no Holocene deformation and masking possible evidence of Pleistocene tectonic activity.

### Sevier Section

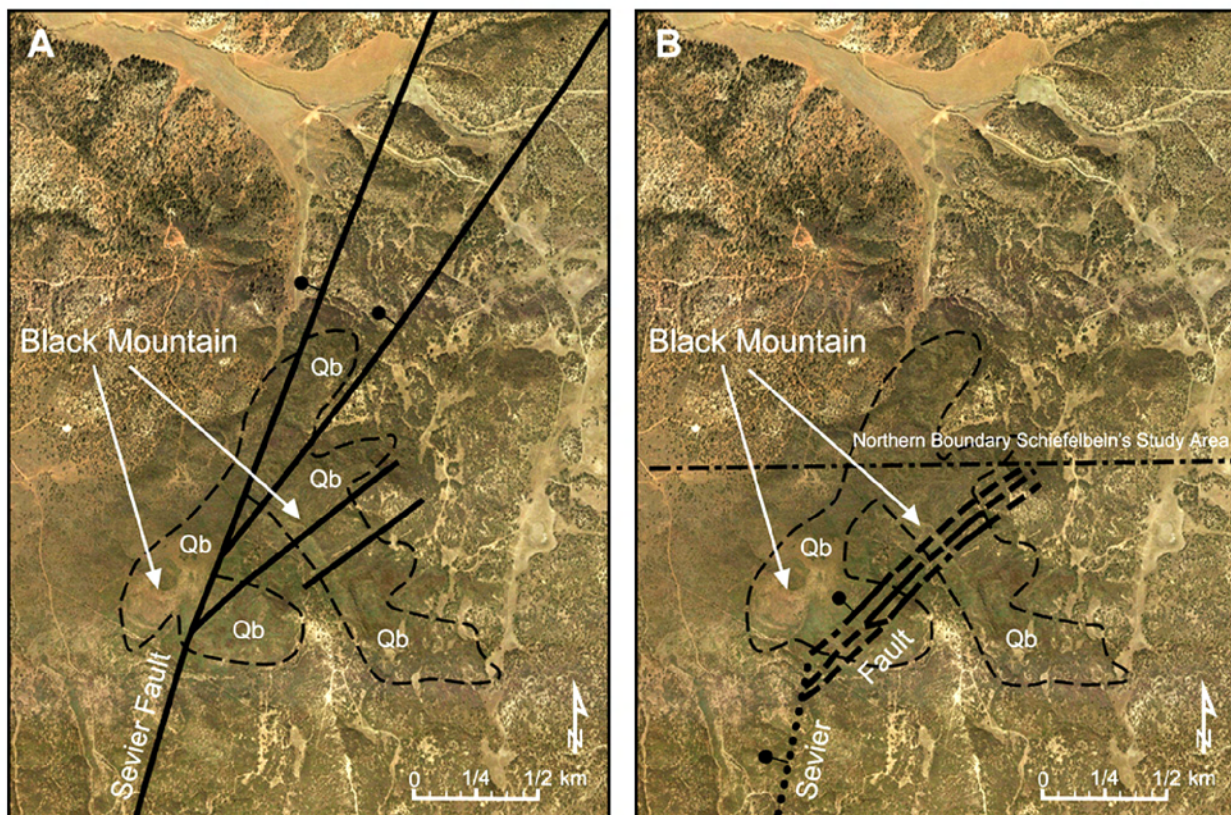
The Sevier section extends for 88 km (straight line) from Clay Flat to northeast of Panguitch where the Sevier fault terminates (figure 2). The Sevier section exhibits a complex pattern of right-stepping, overlapping faults that create a series of relay ramps and local folds between fault strands from Clay Flat to near Black Mountain, a distance of about 27 km (Sargent and Philpott, 1987; Doelling and Davis, 1989; Davis, 1999; Reber and others, 2001; Schiefelbein, 2002). North of Black Mountain the fault trace is less complex, and has been mapped as a single strand in many areas (Doelling, 1975; Doelling and Davis, 1989; Tilton, 2001). However, the Sevier fault has not been mapped in detail (1:24,000 scale) north of the Kane County-Garfield County boundary (figure 2), so as yet unrecognized complexities may exist along the fault.

Doelling and Davis (1989) show strands of the Sevier section cutting both Holocene and Pleistocene unconsolidated deposits at several locations between Clay Flat and Glendale, Utah. Our aerial-photograph interpretation and field

reconnaissance did not verify the displaced deposits shown on the Doelling and Davis (1989) map, nor identify displaced Quaternary deposits elsewhere on the Sevier section in Utah. Additionally, the original geologic maps (Cashion, 1961, 1967; Sargent and Philpott, 1987) from which Doelling and Davis (1989) compiled their map do not show faults cutting unconsolidated Quaternary deposits.

The Sevier section displaces Quaternary volcanic rocks at two locations, Black Mountain in Kane County and Red Canyon, about 44 km (straight line) farther north in Garfield County (Gregory, 1951; Cashion, 1961, 1967; Doelling, 1975; Anderson and Christenson, 1989; Doelling and Davis, 1989; Schiefelbein, 2002; figure 2). Because no scarps are formed on unconsolidated deposits along the main trace of the Sevier fault, these displaced volcanic rocks provide the only opportunity to determine average vertical slip rates for the Sevier section, and therefore are discussed in detail below.

**Black Mountain:** Quaternary volcanic rocks crop out at Black Mountain (sections 28, 29, 32, and 33, T. 39 S., R. 6 W., SLBL; figure 7), and are displaced across the Sevier fault (Cashion, 1961, 1967; Doelling and Davis, 1989; Schiefelbein, 2002). We collected a sample of volcanic rock from the fault footwall and submitted it to the Washington State University GeoAnalytical Laboratory for geochemical analysis (appendix A, sample SF-10). Major- and trace-element analyses identified the rock as a trachybasalt (R.F. Biek, UGS, written communication, 2007). The source of the volcanic rock has not been identified; however, it is likely near-



**Figure 7.** Black Mountain and vicinity showing the trace of the Sevier fault as mapped by (A) Cashion (1961, 1967) and (B) Schiefelbein (2002). Dashed fault line = approximately located, dotted fault line = concealed; bar and ball are on downthrown side of fault; Qb = volcanic rocks. See figure 2 for the location of Black Mountain.

by because a lava flow extends first westward from the base of Black Mountain and then southward along Spencer Bench parallel to the East Fork of the Virgin River for about 2.5 km (Cashion, 1961, 1967). At the time of its eruption, the lava moved west along a tributary to the East Fork of the Virgin River and then south down the ancestral river channel. Subsequent erosion by the river has left the flow capping Spencer Bench 30 m or more above the present river channel.

Cashion (1961) mapped the Sevier fault at Black Mountain (figure 7A), and reported that the volcanic rocks there are displaced 75 feet (23 m) down-to-the-west across the fault. Cashion (1961) did not report where or how he determined the displacement. Best and others (1980) obtained a K-Ar age of  $0.56 \pm 0.06$  Ma for the volcanic rocks, but again exactly where (Black Mountain or Spencer Bench) is not clear. Anderson and Christenson (1989) examined the relation between the volcanic rocks and the fault, but found no definitive evidence that the volcanics are displaced by faulting despite their coincidence with the Sevier fault. They attributed several conspicuous scarps formed on the volcanic rocks to landslide main scarps and state, "Though it is probable that the basalt is displaced at the main [fault] trace, there is considerable uncertainty as to which scarps are related to landslides, pre-flow topography, or faults," and conclude, "These uncertainties preclude estimating long-term displacement rates [at Black Mountain] from available data."

Schiefelbein (2002) conducted a study of fault segmentation, fault linkage, and hazards along a 12-km-long portion of the Sevier fault from south of Orderville to Black Mountain. She mapped four strands of the fault cutting the Black Mountain volcanic rocks (figure 7B), and reported that the volcanics are displaced about 3 m down-to-the-west across the faults (Schiefelbein, 2002, p. 39). She obtained two  $^{40}\text{Ar}/^{39}\text{Ar}$  radiometric ages, one from the volcanic rocks on Black Mountain itself (fault footwall), and one from the lava flow on Spencer Bench (fault hanging wall). The two ages are  $0.58 \pm 0.05$  Ma and  $0.564 \pm 0.02$  Ma, respectively. Using a net vertical displacement of 10 m (Schiefelbein, 2002, p. 58) and an average age of 0.57 Ma for the volcanic rocks, she calculated a vertical slip rate (VSR) ( $\text{VSR} = \text{vertical displacement in mm/time in years}$ ) at Black Mountain of 0.0180 mm/yr. Why a displacement of 10 m was used rather than the 3 m first reported is not known.

Using the newly acquired VSR, Schiefelbein (2002) reported an initiation time for faulting of 44 Ma ( $\text{initiation time of faulting} = \text{total vertical displacement/VSR}$ ), which she considered too old. She stated that the displacement value used to make this calculation is the "greatest amount of stratigraphic separation along the Spencer Bench segment of the main strand of the Sevier fault," but she did not report the actual value. By back-calculating ( $\text{total vertical displacement} = \text{initiation time of faulting} \times \text{VSR}$ ), we obtained a displacement of 790 m. She then attempted to estimate what she considered a more reasonable long-term VSR by assigning all of the displacement near Black Mountain to post-Claron Formation time (past 30 myr). Using that time interval and "the total offset calculated on top of the Jurassic Navajo Sandstone," she calculated a long-term (30 myr) VSR of 0.0229 mm/yr. Again, she did not specify a displacement value, but by back-calculating we determined a vertical displacement of 690 m. Schiefelbein (2002) acknowledged

that if displacement on the Sevier fault initiated significantly later than the end of Claron Formation deposition at 30 Ma, the VSR would be correspondingly higher.

Our aerial-photograph interpretation and field reconnaissance at Black Mountain confirmed Anderson and Christenson's (1989) observations that geologic relations there are complex, exposures are poor, and that pre-basalt topography and landslides are complicating factors. Cashion (1961) and Schiefelbein (2002) reported that the 0.57 Ma volcanic rocks at Black Mountain are displaced 23 and ~3 to 10 m, respectively, across the Sevier fault, both of which result in a low ( $<0.1$  mm/yr) late Quaternary VSR for the fault. Lund (2006) showed that the total elevation difference between the volcanic rocks on top of Black Mountain and those at its base across the fault is approximately 230 m. If that entire elevation difference is attributed to surface faulting, the resulting VSR is 0.40 mm/yr, which is comparable with the 0.36 mm/yr VSR reported by Hecker (1993) for the Sevier fault at Red Canyon in volcanic rocks of approximately the same age 44 km to the north (see below). However, we, like Anderson and Christenson (1989), were unable to resolve how much of the 230 m can be attributed to surface faulting and how much is due to other causes, and therefore could not determine a reliable VSR for the Sevier fault using displaced volcanic rocks at Black Mountain.

Lacking a late Quaternary VSR at Black Mountain, we calculated a long-term VSR for the Sevier fault in a manner similar to that of Schiefelbein (2002). However, we considered Schiefelbein's (2002) 30 Ma estimate for the age of the fault as too old because it significantly predates the onset of regional extensional tectonism in southwestern Utah. Based upon a literature review, Davis (1999) estimated the age of the Sevier fault at 12-15 Ma, an age that is in general agreement with other estimates of the onset of basin-and-range-style faulting in southwestern Utah and surrounding areas. Because geologic relations necessary to better constrain the age of the Sevier fault in Utah are lacking, we adopted Davis' (1999) estimate as a reasonable first-order approximation for the initiation age of the fault. Schiefelbein (2002, p. 36) reported a displacement range across the fault near Black Mountain of 472 to 869 m. We used those displacement values for our VSR calculations, and note that this range incorporates the displacement values of 690 and 790 m obtained by back calculating from Schiefelbein's (2002) long-term VSR estimates (see above).

An age of 12-15 Ma and total displacement of 472 to 869 m yield a middle Miocene to present VSR of 0.03 to 0.07 mm/yr (mean 0.05 mm/yr) for the Sevier fault at Black Mountain. This estimate is low when compared to late Quaternary VSRs on other large, active faults in the eastern Basin and Range Province such as the Hurricane, Paragonah, and Wasatch faults. Late Quaternary rates for those faults range from about 0.2 to  $>1.5$  mm/yr. We do not know if slip on the Sevier fault has remained constant over time or if there have been periods of greater or lesser slip on the fault. Like Schiefelbein (2002), we recognize that should the actual age of the Sevier fault deviate greatly from the Davis (1999) 12-15 Ma age estimate, our VSR estimate would be similarly affected. However, we believe that the Davis (1999) estimate is reasonable, and provides a good first-order approximation of the age of the fault.

Our long-term VSR estimate of 0.03-0.07 mm/yr should



produce 18 to 41 m of displacement of the 0.57 Ma volcanic rocks at Black Mountain. Cashion (1961) reported the volcanics are displaced 23 m, which yields a late Quaternary VSR of 0.04 mm/yr. That rate of slip would displace unconsolidated deposits ranging in age from 5 to 130 ka from 0.2 to 5.2 m ( $\text{displacement} = \text{VSR} \times \text{time in years}$ ). Based on the presence of scarps along the Central Toroweap section in Arizona, which has an estimated slip rate of 0.05-0.075 mm/yr (Jackson, 1990), a VSR of 0.04 mm/yr should produce recognizable scarps on Quaternary deposits near Black Mountain, yet no scarps are present.

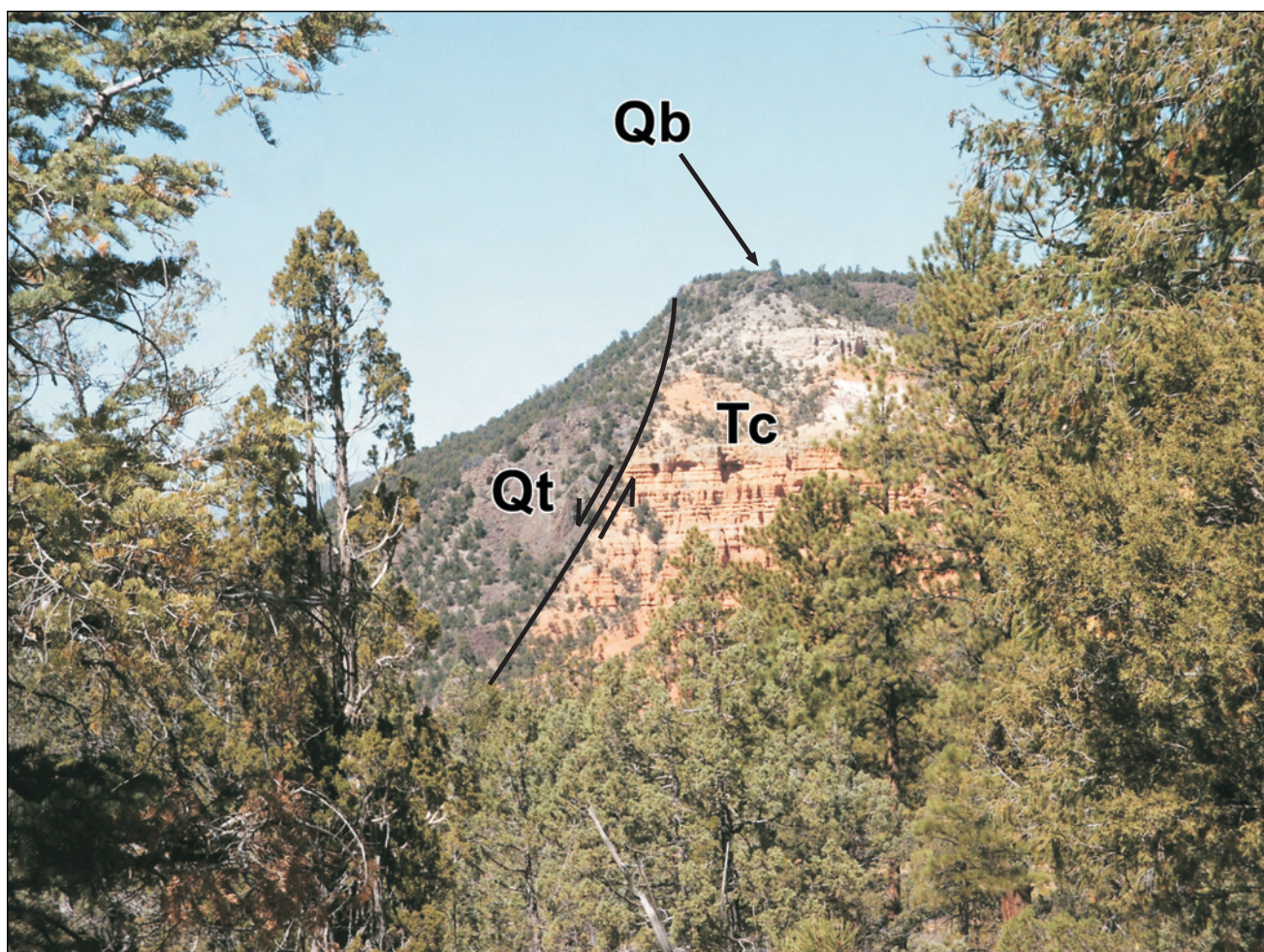
If the average surface faulting displacement on the Sevier fault at Black Mountain is assumed to be 2.0 m, which is typical of many historical surface-faulting earthquakes in the Basin and Range Province, a VSR of 0.04 mm/yr would result in a recurrence interval (RI) for surface faulting of 50 kyr ( $\text{RI} = \text{average slip per event/VSR}$ ). Using our middle Miocene to present VSR estimate of 0.03-0.07 mm/yr yields an RI estimate of 40 kyr (range 29 - 67 kyr). Long intervals between surface-faulting earthquakes are typical of low-slip-rate faults, and likely permit some fault scarps to be obscured by erosion or burial. However, acknowledging that the average surface-faulting displacement on the Sevier fault may be somewhat less than 2.0 m, thus making RIs even longer, it is still difficult to explain why scarps are everywhere absent

along the entire 108-km-long main trace of the Sevier fault in Utah. We conclude that the current VSR at Black Mountain is no greater than our middle Miocene to present estimate of 0.03-0.07 mm/yr, and may be even lower.

**Red Canyon:** The Sevier fault is well exposed at the mouth of Red Canyon immediately north of Utah SR-12 in section 22, T. 35 S., R. 4½ W., SLBL (figures 8 and 9). There, the fault places Quaternary volcanic rocks in contact with red sandstone, siltstone, limestone, and conglomerate of the Eocene Claron Formation. Best and others (1980) obtained a K-Ar age of  $0.56 \pm 0.07$  Ma for the volcanic rocks, and Anderson and Christenson (1989) reported that the volcanics are displaced about 200 m across the fault. Using those data, Hecker (1993) calculated a late Quaternary VSR of 0.36 mm/yr for the Sevier fault at Red Canyon.

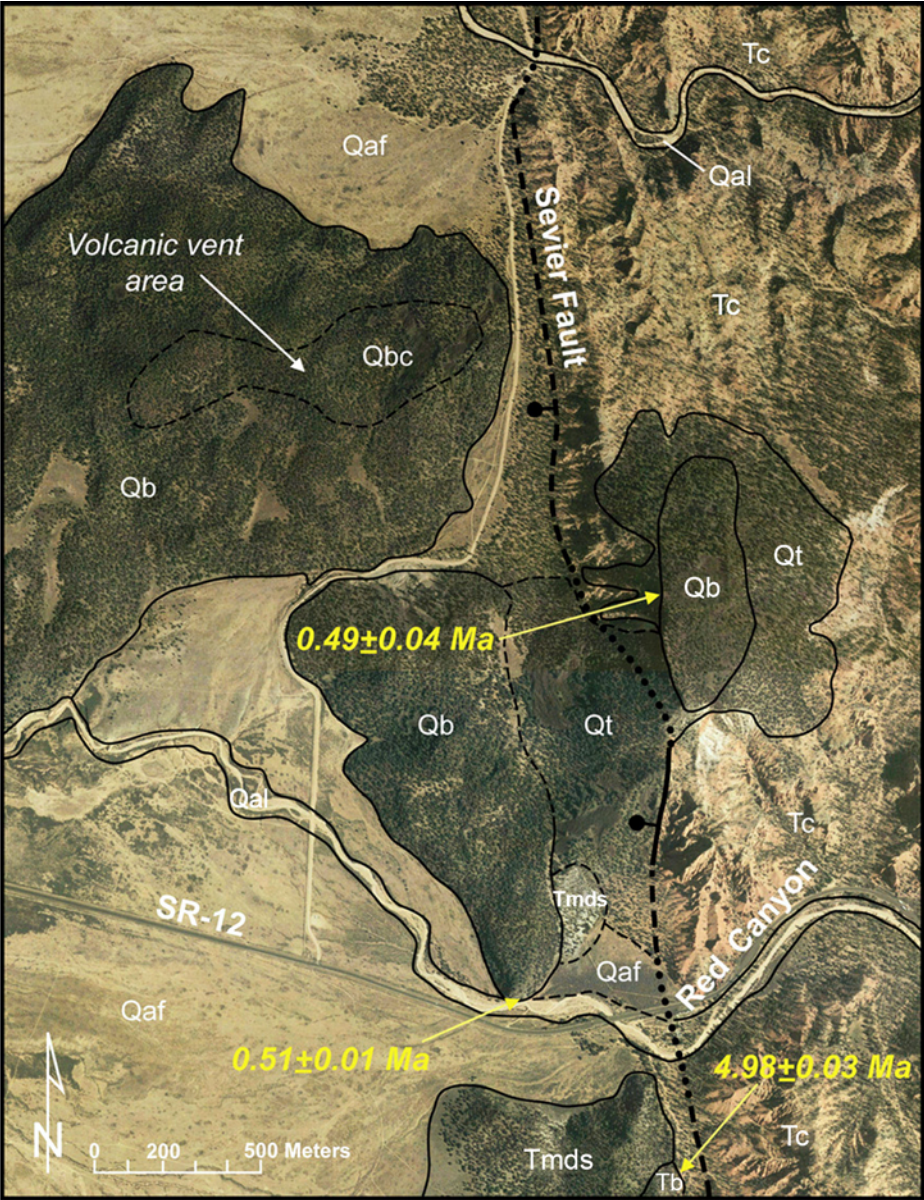
Volcanic rocks also crop out at Red Canyon south of SR-12, on both the footwall and hanging wall of the fault (figure 10; Gregory, 1951). These rocks exhibit a much greater degree of weathering than the volcanic rocks north of SR-12, and are present on the footwall only as isolated outcrops on ridge tops in the Sunset Cliffs (figures 10 and 11).

To further investigate the VSR of the Sevier fault at Red Canyon, we submitted four samples of volcanic rock from the fault footwall and hanging wall to the Geochronology



**Figure 8.** Sevier fault at the mouth of Red Canyon; Qb = Quaternary volcanic flow, Qt = talus, Tc = Claron Formation. View is to the north.





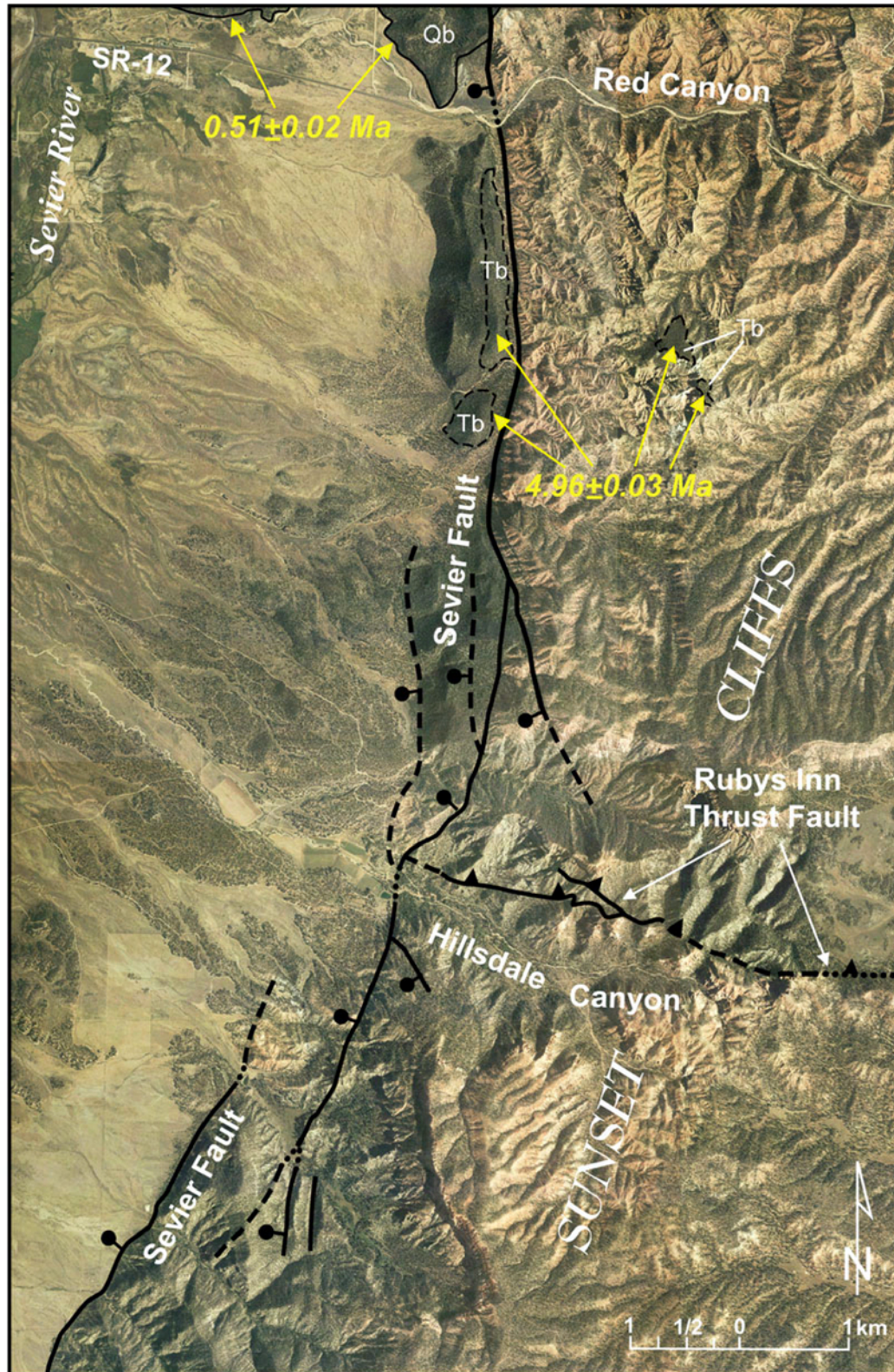
EXPLANATION

- Qal Stream alluvium
- Qaf Fan alluvium
- Qb Mafic volcanic rocks
- Qbc Cinder/spatter cones
- Qt Talus
- Tb Mafic volcanic rocks
- Tmds Mount Dutton volcanic sediments
- Tc Claron Formation

- Geologic unit contact
  - .....
  - Dashed where approximately located, dotted where concealed
- Fault trace
  - .....
  - Dashed where approximately located, dotted where concealed; bar and ball on downthrown side

**Figure 9.** Photogeologic map of the mouth of Red Canyon (after Gregory, 1951; Doelling, 1975). New  $^{40}\text{Ar}/^{39}\text{Ar}$  radiometric ages show that the volcanic rocks south of SR-12 are Tertiary and not Quaternary in age as previously thought. Volcanic vent area is likely source of displaced Quaternary volcanic rocks north of SR-12. See figure 2 for location of Red Canyon.





**Figure 10.** Photogeologic map of Red Canyon and vicinity showing the relation of the older volcanic rocks (Tb) south of SR-12 to each other across the Sevier fault and to the younger volcanic rocks (Qb) north of SR-12, and the relation between the Sevier fault and the Rubys Inn thrust fault (part of the Paunsaugunt thrust system; see figure 17) at Hillsdale Canyon. Ages reported for both groups of volcanic rocks are weighted averages. See figure 2 for the location of Red and Hillsdale Canyons.





**Figure 11.** Outcrop of early Pliocene volcanic rocks (gray) in the footwall of the Sevier fault caps a ridge in the Sunset Cliffs near Red Canyon. View is to the northwest.

Research Laboratory at the New Mexico Institute of Mining and Technology for  $^{40}\text{Ar}/^{39}\text{Ar}$  radiometric age analysis. We submitted duplicate samples to the Washington State University GeoAnalytical Laboratory for major- and trace-element analyses. Two of the samples, one each from the footwall and hanging wall (figure 9), came from the volcanic rocks north of SR-12 previously dated by Best and others (1980). The other two samples came from the volcanic rocks on either side of the fault south of SR-12 (figure 10). Results of the radiometric age analyses are reported in table 1, and results of the geochemical analyses are reported in appendix A.

The new radiometric ages show that (1) there is an approximate ten-fold difference in the age of the volcanic rocks north and south of SR-12, and (2) the new  $^{40}\text{Ar}/^{39}\text{Ar}$  ages for the rocks north of SR-12 are about 50 kyr younger than the K-Ar age obtained by Best and others (1980). We prefer the new  $^{40}\text{Ar}/^{39}\text{Ar}$  ages because (1) we have two corroborating ages, and (2) we know the exact locations from which we collected the dated samples. The geochemical analyses show that the younger volcanic rocks north of SR-12 are trachyandesite whereas the older rocks south of SR-12 are trachybasalt (R.F. Biek, UGS, written communication, 2007).

Hooper (2000) demonstrated that individual volcanic flows can be correlated over long distances using certain geochemical parameters. He worked extensively on the Columbia River basalts where individual flows are traceable for long distances in outcrop. He sampled numerous locations along individual flows and analyzed the samples to determine if certain geochemical characteristics were identifiable along the entire length of the flow. He analyzed for 27 different elements for each sample; however, only a few minor and trace elements were found to be relatively consis-

tent throughout the entire length of a flow; these included  $\text{P}_2\text{O}_5$ ,  $\text{TiO}_2$ , Cr, Zr, Sr, and Ba. The level of confidence is extremely high when making such correlations based on these elements since the geochemical signature is unique for each flow within a very small range. Lund and others (2007) used Hooper's technique to evaluate volcanic rocks on either side of the Hurricane fault in southwestern Utah. The technique proved highly successful in demonstrating the correlation or lack thereof of several basalt flows on either side of that fault. R.F. Biek (UGS, written communication, 2007) prepared variation diagrams (appendix B) for Ba vs. Cr, Nb vs. Nd, Sr vs. Rb, Sr vs. Zr,  $\text{Na}_2\text{O}+\text{K}_2\text{O}$  vs.  $\text{SiO}_2$ , and  $\text{TiO}_2$  vs.  $\text{P}_2\text{O}_5$ . The diagrams show a close correlation between samples SF-1 and SF-3 collected from the young volcanic rocks north of SR-12 and between samples SF-5 and SF-8 collected from the older volcanic rocks south of SR-12. The two sample sets are chemically distinct from each other. Based on these results, Biek concluded that the younger volcanic rocks on either side of the Sevier fault north of SR-12 are correlative, as are the older volcanic rocks south of SR-12.

Calculating a VSR using displaced volcanic flows requires that the source of the flows be known. Flows erupting on the fault footwall may cascade over a pre-existing fault escarpment onto the hanging wall and create the impression of greater displacement than has actually occurred due to faulting. If cascading occurs and the flows are subsequently displaced by surface faulting, a VSR determined using the elevation difference between outcrops across the fault will be erroneously high.

We conducted a literature search, aerial-photograph interpretation, and field reconnaissance at Red Canyon to identify the source of the volcanic rocks both north and south of SR-12. Our results show that:

**Table 1.**  $^{40}\text{Ar}/^{39}\text{Ar}$  radiometric age analyses of mafic volcanic rocks that crop out in the footwall and hanging wall of the Sevier fault at Red Canyon, Garfield County, Utah.

Sample Number	Location	UTM Coordinates	$^{40}\text{Ar}/^{39}\text{Ar}$ Radiometric Age	Comments
SF-2	Footwall north side SR-12	12 S 0382905 4179193	$0.49 \pm 0.04$ Ma	Base of flow rests on bedded fluvial deposit consisting mostly of volcanic cinders.
SF-6	Hanging wall north side of SR-12	12 S 0382971 4178977	$0.51 \pm 0.01$ Ma	Base of flow rests on coarse fluvial deposit.
SF-4	Footwall south side SR-12	12 S 0384650 4175800	$4.94 \pm 0.03$ Ma	Base of flow rests on coarse, rounded, mostly volcanic clasts of Mount Dutton Fm.?
SF-7	Hanging wall south side of SR-12	12 S 0382781 4177619	$4.98 \pm 0.03$ Ma	Base of flow obscured by talus.

- (1) There is no discernable source for volcanic rocks of either age in the fault footwall.
- (2) The conspicuous white outcrop beneath the volcanic rocks in the fault footwall north of SR-12 (figure 12) is not the “white Claron” subunit of the Claron Formation (Gregory, 1951; Doelling, 1975), but more likely is an erosional remnant of the conglomerate at Boat Mesa of Bowers (1990) from lower in the Claron section (G.C. Willis and R.F. Biek, UGS, verbal communication, 2004).
- (3) The fine-grained white sandstone exposed in the fault hanging wall at the base of the fault escarpment north of SR-12 contains flecks of biotite and is likely part of the Mount Dutton volcanics, and therefore is not the stratigraphic equivalent of the white, non-biotite-bearing unit (conglomerate at Boat Mesa) in the fault footwall. Thus, the difference in elevation between the two white units cannot be used to determine displacement across the Sevier fault.
- (4) A previously unrecognized eroded cinder cone or group of spatter cones associated with the younger volcanic rocks is present on the Sevier fault hanging wall north of Utah SR-12 (figure 9).
- (5) A mafic volcanic flow overlies Tertiary valley-fill deposits west of the Sevier River about 4.6 km north of Hatch along U.S. Hwy 89 (Anderson and Christenson, 1989; figure 13). This flow is thought to have originated from a source farther west on the Markagunt Plateau; H. Mehnert (written communication, 1988, reported in Anderson and Christenson, 1989) dated the flow at 5.3 Ma.

Identification of a possible hanging-wall source for the younger volcanic rocks at Red Canyon indicates that lava from the cinder/spatter cone(s) likely flowed to a pre-existing fault escarpment, and then flowed across the Sevier fault and a short distance up a drainage crossing the escarpment. Subsequent surface faulting over the past approximately half million years has displaced the flow, leaving volcanic rocks stranded on the fault footwall. This scenario implies that the 192–225 m difference in elevation we measured between the volcanic rocks on either side of the Sevier fault north of SR-12 is entirely due to post-eruption surface faulting. Using a new average age for the younger volcanics of  $0.51 \pm 0.02$  Ma (weighted mean of the two new  $^{40}\text{Ar}/^{39}\text{Ar}$  ages) and the displacement data above, we calculated a late Quaternary VSR estimate for the fault at Red Canyon of 0.38–0.44 mm/yr (mean 0.41 mm/yr).

The weighted mean age of the volcanic rocks south of SR-12 is  $4.96 \pm 0.03$  Ma. The elevation difference between the top of the highest volcanic outcrop on the fault footwall and the top of the corresponding volcanic outcrops on the hanging wall (base of volcanics not exposed in fault hanging wall, so it was necessary to use the less reliable top of the flows to measure displacement) ranges from about 237 to 344 m. Although the older volcanic rocks south of SR-12 are not immediately juxtaposed across the fault in a manner similar to the younger volcanics north of SR-12, they are indistinguishable on the basis of age and chemistry and are thought to represent the same flow, which likely originated from the west where other volcanic rocks of similar age are present. These new age and displacement data yield an early Pliocene to present VSR estimate at Red Canyon of 0.05–0.07 mm/yr (mean 0.06 mm/yr).

Lundin (1989) states that seismic reflection data show about 900 m of throw on basement rocks across the Sevier fault at Red Canyon. Using that displacement and the Davis (1999) 12–15 Ma age estimate for initiation of the Sevier fault yields a middle Miocene to present VSR estimate at Red Canyon of 0.06–0.08 mm/yr (mean 0.07 mm/yr), which





**Figure 12.** Outcrop of the conglomerate at Boat Mesa (white) beneath volcanic rocks (gray) in the footwall of the Sevier fault at the mouth of Red Canyon north of SR-12. The conglomerate at Boat Mesa is lower in the Claron Formation section than is the “white Claron,” with which this unit is frequently confused. View is to the northeast.



**Figure 13.** Volcanic flow exposed in a road cut along U.S. Hwy 89 about 5 km north of Hatch, Utah (MP~118.5). This flow has been dated at 5.3 Ma and is thought to be from a source farther to the west on the Markagunt Plateau. View is to the northeast.



is roughly similar to the upper bound of the middle Miocene to present VSR estimate (0.03-0.07 mm/yr) at Black Mountain.

Again assuming an average surface-faulting displacement of 2.0 m on the Sevier fault, we calculated RI estimates at Red Canyon of 4.4-5.3 kyr (mean 4.9 kyr) for the late Pleistocene, 29-40 kyr (mean 35 kyr) since the early Pliocene, and 25-33 kyr (mean 29 kyr) since the middle Miocene.

The middle Miocene to present and early Pliocene to present VSR estimates at Red Canyon are lower than the late Pleistocene VSR by roughly a factor of six. Lund and others (2007) documented a change in VSR over time on the Hurricane fault elsewhere in southwestern Utah, so a change in the rate of slip on the Sevier fault appears permissible. However, a comparatively high late Quaternary VSR is at odds with the absence of scarps on unconsolidated deposits at Red Canyon, where a VSR of 0.38-0.44 mm/yr acting over a period of 5 to 130 kyr on what is essentially a single fault strand should produce scarps on unconsolidated deposits ranging from about 2 to 58 m high. However, even in the absence of recognizable scarps on unconsolidated deposits, the evidence for a higher late Pleistocene VSR at Red Canyon is compelling. The displaced younger volcanic rocks are immediately juxtaposed across the fault, their ages and chemical compositions are indistinguishable, and we identified a likely volcanic source on the fault hanging wall. The possibility remains that the source for the younger volcanic flow was in fact on the fault footwall, and that the flow cascaded over a pre-existing escarpment. However, evidence for a footwall volcanic source is lacking (possibly removed by subsequent erosion), and therefore, until evidence is presented to the contrary, we must conclude that the current VSR on the Sevier fault at Red Canyon is in fact higher than the two longer term rates.

### **Sevier Valley (Hills Near Panguitch) Faults and Folds**

A diffuse zone of broad anticlines and synclines and generally fold-parallel fault scarps, many forming narrow key-stone grabens at anticlinal crests, extends for about 23 km from the hills south of Panguitch northeastward across the Sevier River to east of Panguitch (figure 2). The faults and folds are in the hanging wall of the Sevier fault and the deformed deposits range in age from late Tertiary to late Pleistocene (Anderson and Christenson, 1989; Moore and Straub, 1995; Kurlich and Anderson, 1997). The numerous scarps are conspicuous on aerial photographs (figure 14) and range from less than a meter to more than 25 m high.

The northernmost northeast-trending anticline deforms fan surfaces extending westward from the Sunset Cliffs (Sevier fault escarpment) that are probably as old as middle Pleistocene (Anderson and Christenson, 1989). The fold rotates the fan surfaces a few degrees away from a central graben (Racetrack Hollow; figure 14). North-trending anticlines to the south in the Panguitch Hills are also faulted, have limbs that dip an average of 5°, and locally deform a 5.3 Ma basalt flow (H. Mehnert, written communication, 1988, reported in Anderson and Christenson, 1989 [figure 13]). Two scarps on the east side of the Sevier River (sections 11 and 12, T. 35 S., R. 5 W., SLBL) about 4 km north of the U.S. Hwy 89 and Utah SR-12 intersection (figure 14) each dis-

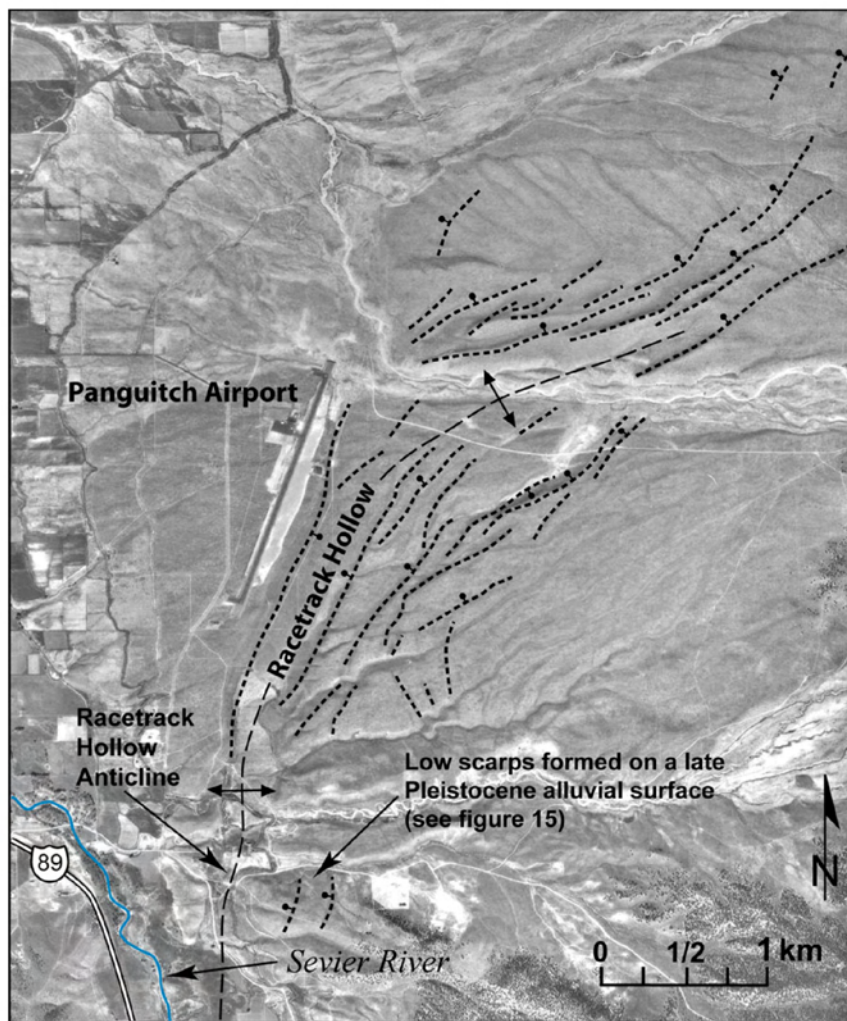
place a probable late Pleistocene alluvial surface less than a meter (figure 15), and appear to be the youngest faults in the zone. Several small closed basins that disrupt drain-ages in the Panguitch Hills (Anderson and Christenson, 1989) and an anomaly in the channel of the Sevier River (Harbor, 1998) indicate that deformation within the fault-and-fold zone is ongoing. Anderson and Christenson (1989) reported that deformation resulting from folding far exceeds that due to faulting, and that the fault-and-fold zone is an area of net uplift. According to Anderson and Christenson (1989) the faults and folds formed aseismically and are related to the subparallel Sevier fault, which at its closest point lies 1 km to the east, but typically is 5 to 8 km distant from the fault-and-fold zone.

Many of the scarps and associated grabens in the fault-and-fold zone have good access and are suitable for trenching. The age of the faults and folds is not known, but the wide range in scarp heights suggests a similar wide range in age and number of possible surface-faulting earthquakes. However, the origin of the scarps is uncertain; whether the scarps are the result of surface faulting, or formed in response to aseismic deformation, is unknown. In either case, trenching the scarps would reveal little about surface faulting on the main Sevier fault to the east. If the scarps resulted from surface faulting, establishing a comprehensive paleoearthquake chronology for the entire fault-and-fold zone would require trenching several scarps. In the absence of a viable trench site (due to the absence of scarps) on the main Sevier fault for comparison, the relation between the timing of surface faulting within the fault-and-fold zone and the main Sevier fault would remain unresolved. Conversely, if the hanging-wall faults are the result of aseismic folding, subsequent scarp erosion would likely not produce the individual scarp-derived colluvial wedges that are typical of surface faulting (Schwartz and Coppersmith, 1984; Machette and others, 1992; McCalpin, 1996; Ferrelly and others, 2002). In that case, trenching would confirm only that the scarps did not result from coseismic surface faulting.

### **Sevier Valley (North of Panguitch) Faults**

Anderson and Rowley (1987) mapped a short (6 km) zone of northeast-trending normal faults in the floor of Sevier Valley near Sanford Creek north of Panguitch (figure 2). The faults displace unconsolidated Quaternary deposits and form a conspicuous horst on the east side of the Sevier River (figure 16). Scarps within the zone vary in height depending upon the age of the deposits displaced, and are as high as 12 m on surfaces thought to be as old as middle Pleistocene and less than a meter high on surfaces of probable late Pleistocene age (Anderson and Christenson, 1989).

Anderson and Christenson (1989) made a photo-log of a fault exposure in the wall of a commercial wood-chip disposal pit, and reported evidence for two surface-faulting earthquakes. Uncertainties regarding the relation between soil development and the most recent surface-faulting earthquake, and a lack of datable organic material in the fault exposure prevented the determination of earthquake timing. The most recent surface faulting displaced a middle to late Pleistocene alluvial surface about 80 cm, which along with age estimates obtained by Bucknam and Anderson (1979) by regressing scarp-slope angle on log scarp height from scarp

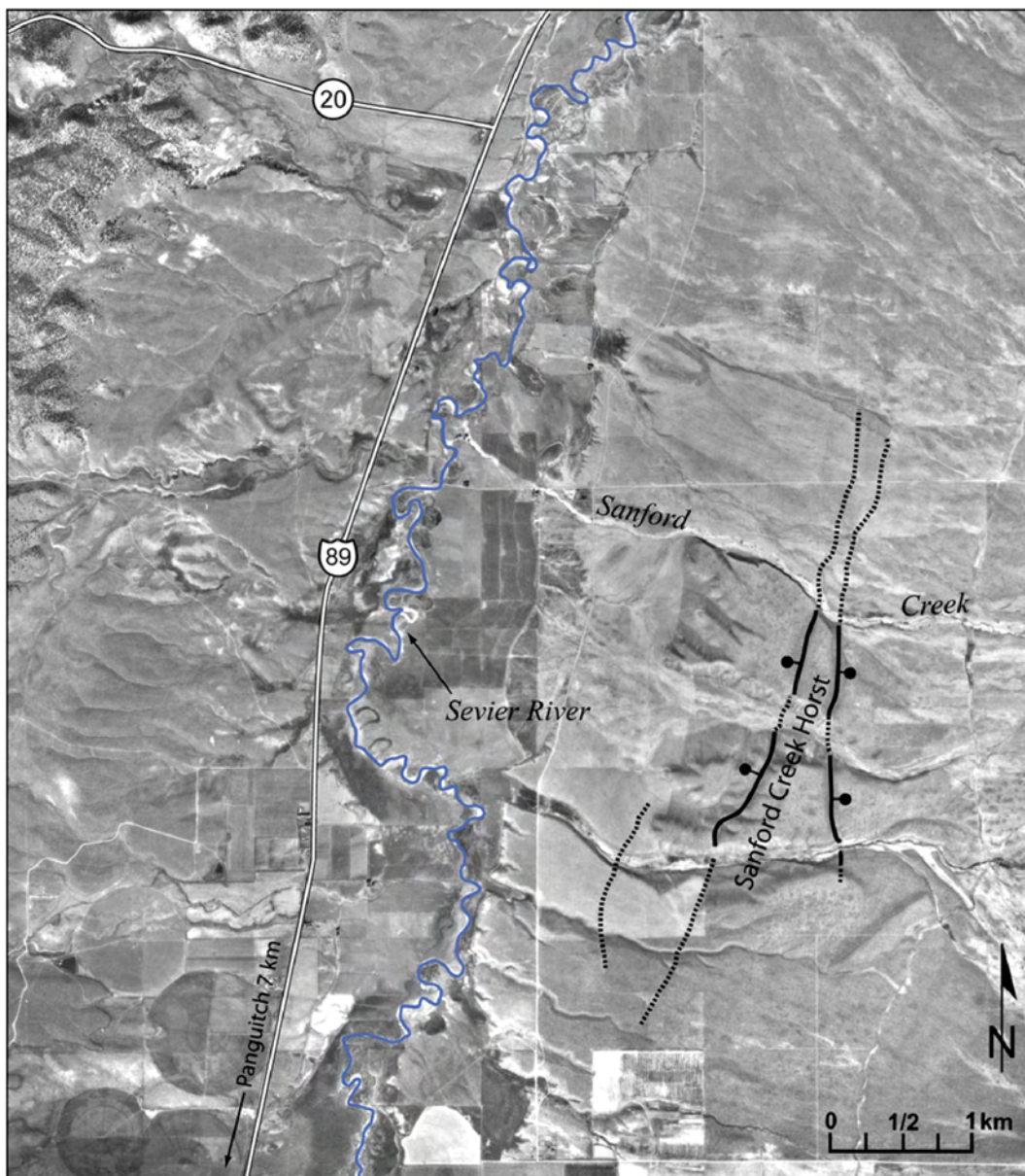


**Figure 14.** Faults and folds formed on middle to late Pleistocene alluvial deposits in the Sevier fault hanging wall near Panguitch, Utah. The scarps range from < 1 m to several meters high and define a NE-trending zone ~24 km long associated with an active fold belt. The scarps commonly form keystone grabens along fold crests, such as at Racetrack Hollow. Ball and bar on downthrown side of fault, dashed where approximately located. See figure 2 for location of fault-and-fold belt.

**Figure 15.** Low, gentle scarp formed on a late Pleistocene alluvial surface a few meters above the present Sevier River flood plain south of Panguitch, Utah (see figure 14). View is to the east.







**Figure 16.** Sanford Creek fault zone and horst northeast of Panguitch in the hanging wall of the Sevier fault; ball and bar on downthrown side of fault, dashed where approximately located. See figure 2 for location of these faults north of Panguitch.

profiles, caused Anderson and Christenson (1989) to suggest a late Pleistocene age for that earthquake. The older earthquake produced about 60 cm of displacement and pre-dates formation of the middle to late Pleistocene alluvial surface. Anderson and Rowley (1989) reported vegetation lineaments in Holocene stream-channel deposits as evidence of Holocene faulting. However, Anderson and Christenson (1989) disagreed and stated that the lineaments are an expression of ground water concentrated along buried portions of late Pleistocene faults.

The fault zone near Sanford Creek appears to be related to tectonic surface faulting. However, the height of the scarps (12 m maximum) and short fault length (6 km end to end) is anomalous. A fault exhibiting 12-m-high scarps would normally be expected to have a rupture length considerably greater than 6 km (Wells and Coppersmith, 1994). Anderson and Rowley (1987) stated that the northern Sevier

Valley is an area of a “great amount of dissection” that probably exceeds 20 ft (6 m) in historical time. Therefore, erosion since the late Pleistocene may have removed evidence of a more extensive fault zone. Conversely, the 12-m scarp may represent many (15-20) 60-80 cm surface-faulting events since the middle Pleistocene. Why the scarps would have been preferentially preserved in an otherwise rapidly eroding area is unknown.

Our investigation showed that sites suitable for trenching exist on both multiple- and probable single-event fault scarps in the Sanford Creek area. However, it is unclear what relation surface faulting on this short fault zone has to faulting on the much larger Sevier fault several kilometers to the east. In the absence of a viable trench site on the main fault (see above) for comparison, the relation between the timing of surface faulting within the Sanford Creek fault zone and the main Sevier fault would remain unresolved.

## DISCUSSION

### Paleoearthquake Timing and Displacement

The absence of scarps on unconsolidated deposits along the Sevier fault in Utah precludes using paleoseismic trenching techniques to determine the timing and displacement of individual paleoearthquakes. Trenching scarps on unconsolidated Quaternary deposits in the Sevier fault hanging wall near Panguitch is possible, but the relation, if any, of those scarps to surface faulting or to the main Sevier fault is unknown. Consequently, the only opportunity to develop individual paleoearthquake timing and displacement information relevant to the Sevier fault in Utah is by trenching scarps on unconsolidated deposits on the Northern Toroweap section in Arizona. No scarps are present on the Sevier section, so individual paleoearthquake timing and displacement information will remain unavailable for that fault section.

### Vertical Slip Rate and Average Recurrence Interval

Because displacement and timing information cannot be developed for individual Sevier fault paleoearthquakes, VSR and RI estimates must be obtained from information about the age and displacement of volcanic rocks along the fault, or from estimates of total displacement since the initiation of faulting (see above). The resulting VSR and RI estimates are based on long time intervals (minimum 0.5 myr) and open seismic cycles (displacement not constrained between paleoearthquakes of known age). Because the time intervals over which we determined our new VSR and RI estimates are long and typically exceed our RI estimates by a factor of 100 or more, we consider the effect of the open seismic cycles on our VSR and RI estimates to be minimal. Available VSR and RI information for the Sevier fault is summarized in table 2.

Table 2 shows that with the exception of the VSR obtained from the late Pleistocene trachyandesite flow displaced across the Sevier fault north of SR-12 at Red Canyon, VSR estimates for the Sevier and Northern Toroweap sections of the Sevier fault in Utah and the Northern Toroweap section in Arizona are consistently  $<0.1$  mm/yr. Unconsolidated deposits overlying the Sevier fault are not abundant in Utah, but such deposits are present locally and potentially could be displaced. These deposits likely range in age from late Holocene ( $\leq 5$  kyr) to late Pleistocene ( $\leq 130$  kyr) and may be as old as middle Pleistocene in some places. Jackson (1990) reported a rough long-term VSR for the Central Toroweap section in Arizona of 0.05 - 0.075 mm/yr. He based his slip rate on 6.5 m of vertical displacement of late Pleistocene ( $\sim 25$ -100 ka) alluvium, 15 m of displacement of a 200 ka basalt flow, and 36 m of displacement of a 600 ka basalt flow. In his compilation, Pearthree (1998) estimated a long-term VSR for the Central Toroweap section of 0.05-0.075 mm/yr based on Jackson (1990). Fenton and others (2001a, 2001b) used cosmogenic isotope dating techniques to calculate VSRs on the Central Toroweap section near the Grand Canyon where scarps are formed on lava flows, cinder cones, and alluvial deposits; they report VSRs ranging from 0.07 to 0.18 mm/yr. It is interesting to note that a VSR between 0.05 and 0.18 mm/yr on the Central Toroweap section produced numerous recognizable fault scarps. Similarly, Pearthree (1998) reported a single, rough VSR estimate of

0.01-0.04 mm/yr for the Northern Toroweap section based on displacement of late Pleistocene alluvium in Arizona.

The absence of scarps on unconsolidated deposits everywhere along the main trace of the Sevier fault in Utah, and the presence of only a single low scarp on Pleistocene alluvial deposits on the Northern Toroweap section in Arizona, supports a low VSR and correspondingly long RI for the Sevier fault. However, even at these low rates, scarps on late Pleistocene (130 ka) deposits should be meters to more than 10 m high. The absence of scarps argues for one or more of the following conditions to exist (1) the current VSR for most of the fault is less than or equal to our long-term VSR estimates, and the rates of erosion and burial obscure scarps on unconsolidated deposits due to the long recurrence intervals between surface-faulting earthquakes, (2) all unconsolidated deposits overlying the fault in Utah are younger than the most recent surface-faulting earthquake, or (3) surface faulting is constrained everywhere along the fault to the immediate bedrock-alluvium interface or is limited entirely to bedrock. Of these three possibilities, we consider the first to be the most likely explanation for the absence of scarps on the fault in Utah. We believe that a VSR greater than 0.1 mm/yr, and surely a rate of 0.4 mm/yr (maximum allowed by the difference in elevation of volcanic rocks across the fault at Black Mountain; Lund, 2006) is unlikely for most of the fault since such comparatively high VSRs would almost certainly produce recognizable scarps on unconsolidated deposits.

The late Pleistocene VSR (0.38-0.44 mm/yr) recorded by displaced younger volcanic rocks at Red Canyon is significantly higher than the middle Miocene to present (0.06-0.08 mm/yr) and early Pliocene to present (0.05-0.07 mm/yr) VSR estimates at that same location, and likewise is higher than the VSR estimates obtained at other places along the Sevier fault as well (table 2). While seemingly anomalous, the faster rate is well supported by available geologic evidence and is difficult to discount. Given the faster rate, the absence of scarps on unconsolidated deposits at Red Canyon is especially puzzling. Possible reasons for the lack of scarps include (1) the source of the younger volcanic rocks is actually on the fault footwall where all evidence has been removed by post-eruption erosion, and the flow cascaded over a pre-existing bedrock fault escarpment, (2) the rate of erosion and burial at Red Canyon is faster than the fault's ability to create scarps even at the higher slip rate, and all traces of fault scarps disappear within a few thousand years, or (3) as noted above, surface faulting is everywhere constrained along the fault to the immediate bedrock-alluvium interface or is limited entirely to bedrock, making scarps difficult to recognize. Which, if any, of the above explanations is correct is not known, but based on the results of this investigation, we cannot discount the comparatively high late Pleistocene VSR and correspondingly shorter RI on the Sevier fault at Red Canyon.

### Segmentation

For convenience, previous workers have subdivided the Sevier fault into sections (e.g., the Northern Toroweap and Sevier sections) based on a range of characteristics such as fault activity, topographic and fault geometry, and political boundaries (Pearthree, 1998; Black and others, 2003). His-

**Table 2.** Vertical slip rate (VSR) and surface-faulting recurrence-interval (RI) information for the Sevier fault in Utah and northern Arizona.

Location	Reference	Time Interval	VSR (range) mm/yr	RI (range) kyr <sup>1</sup>	Remarks
<b>Northern Toroweap Section</b>					
Arizona	Pearthree (1998)	late Pleistocene (~50-150 ka)	0.01-0.04	None reported	2 m vertical displacement across a fault scarp on alluvium
Utah			None	None	No scarps on unconsolidated deposits in Utah.
<b>Sevier Section</b>					
Black Mountain	Schiefelbein (2002)	$0.57 \pm 0.02^2$ myr	0.0180	None reported	Based on 10 m of vertical displacement of volcanic rocks at Black Mountain
Black Mountain	Schiefelbein (2002)	30 myr <sup>3</sup>	0.0229	None reported	30 myr interval based on the age of the upper contact of the Eocene Claron Formation
Black Mountain	This report	$0.57 \pm 0.02^2$ myr	0.04	50	Based on 23 m of vertical displacement (Cashion, 1961) of volcanic rocks at Black Mountain
Black Mountain	This report	12-15 myr <sup>4</sup>	0.05 (0.03-0.07)	40 (29 - 67)	The absence of scarps on unconsolidated deposits along the SS implies a low VSR and long RI
Red Canyon	Hecker (1993)	$0.56 \pm 0.06^5$ myr	0.36	None reported	Based on 200 m <sup>6</sup> of net vertical displacement in late Quaternary volcanic rocks north of SR-12
Red Canyon	This report	$0.51 \pm 0.02^7$ myr	0.41 (0.38-0.44)	4.8 (4.4 – 5.3)	Based on 192–225 m of net vertical displacement in late Quaternary volcanic rocks north of SR-12
Red Canyon	This report	$4.96 \pm 0.03^8$ myr	0.06 (0.05-0.07)	33 (29 – 40)	Based on 237–344 m of net vertical displacement in early Pliocene volcanic rocks south of SR-12
Red Canyon	This Report	12-15 myr <sup>4</sup>	0.07 (0.06-0.08)	29 (25 – 33)	Based on 900 m of vertical displacement in basement rocks at Red Canyon
<sup>1</sup> All RIs are estimates based on an assumed 2.0 m average vertical displacement during a surface-faulting earthquake on the SF; actual RIs would vary if the average displacement is greater or less than 2.0 m. <sup>2</sup> Weighted average of the two new <sup>40</sup> Ar/ <sup>39</sup> Ar radiometric ages obtained by Schiefelbein (2002) at Black Mountain. <sup>3</sup> Estimated age of the upper contact of the Eocene Claron Formation based on the age of a volcanic ash horizon within the formation (Schiefelbein, 2002). <sup>4</sup> Estimated timing of the initiation of faulting on the Sevier fault (Davis, 1999). <sup>5</sup> K-Ar radiometric age obtained by Best and others (1980) for the displaced volcanic rocks north of SR-12. <sup>6</sup> From Anderson and Christenson (1989). <sup>7</sup> Weighted average of the two new <sup>40</sup> Ar/ <sup>39</sup> Ar radiometric ages obtained during this investigation for the volcanic rocks north of SR-12. <sup>8</sup> Average age of the two new <sup>40</sup> Ar/ <sup>39</sup> Ar radiometric ages obtained during this investigation for the volcanic rocks south of SR-12; variation for both ages was the same, $\pm 0.03$ mm/yr, so calculating a weighted average was not necessary.					

torical surface-faulting earthquakes and paleoseismic studies have shown that long normal-slip faults in the Basin and Range Province rupture in shorter segments rather than over their entire length. Because individual segment earthquakes rupture only part of the fault, the earthquakes are smaller than would be the case if the entire fault ruptured. For earthquake-hazard assessment, it is necessary to identify seismogenic segments that rupture independently during earthquakes (Schwartz and Coppersmith, 1984; Crone and Haller, 1991; dePolo and others, 1991; Wheeler and Krystinik, 1992; Zhang and others, 1999). Because the segments are independently seismogenic, they each develop an independent surface-faulting history. Seismogenic segments are separat-

ed from adjoining segments by boundaries that may either be persistent (consistently stop surface rupture) or nonpersistent (sometimes allow rupture overlap between segments or allow multiple-segment ruptures; Wheeler and Krystinik, 1992).

Machette and others (1992) compiled lengths of historical normal-slip earthquake surface ruptures in the Basin and Range Province. The rupture lengths range from as little as 11 km for the  $M_s$  6.6 Hansel Valley, Utah, earthquake, to as much as 62 km for the  $M_s$  7.1 Fairview Peak and  $M_s$  7.6 Pleasant Valley, Nevada, earthquakes. The Wasatch fault in northern Utah is the longest and most extensively studied active fault in the Basin and Range Province. The results of numerous paleoseismic trenching investigations show that



the Wasatch fault is subdivided into 10 seismogenic segments having lengths ranging from 11 to almost 70 km, and that the average length of the six segments having surface faulting during the Holocene is 48 km (Machette and others, 1992). Machette and others (1992) also report segment lengths for six additional active normal faults in the western United States. The longest reported segment does not exceed 45 km, and average segment lengths for the faults range from 13 to 26 km. In comparison, Pearthree (1998) reported a length of 60 km for the Northern Toroweap section in Arizona, and Black and others (2003) reported that the Northern Toroweap section continues for an additional 20 km into Utah for a total length of 80 km. Similarly, Black and others (2003) reported a length of 88 km for the Sevier section in Utah. Considering historical surface-faulting rupture lengths of Basin and Range faults, and the significantly greater lengths of the Northern Toroweap and Sevier sections, we consider it unlikely that either section represents a single seismogenic segment, and believe it is more likely that the Sevier fault ruptures in shorter segments in a manner similar to other Basin and Range normal faults.

Seismogenic segment boundaries may take many forms including en echelon steps, salients, geometric bends, gaps in faulting, T-junctions, and intersections of cross structures with the active fault trace (Crone and Haller, 1991; Machette and others, 1992; Wheeler and Krystinik, 1992; Zhang and others, 1999). Stratigraphic, Bouguer gravity, and aeromagnetic studies have been extremely useful in identifying segments of large Basin and Range faults (e.g., Wasatch fault, Lost River fault zone). Steep gradients and saddles in geophysical data may reveal discrete sediment-filled structural basins that have developed above individual seismogenic segments. Unfortunately, the Sevier fault in much of Utah parallels the actively downcutting headwaters of the Sevier and Virgin Rivers, creating an erosion-dominated regime lacking hanging-wall depositional basins. Thus, geophysical data in the region are generally featureless and provide little help defining segmentation (Cook and others, 1989; Bankey and others, 1998). However, based on available geologic data, we have identified three possible seismogenic segment boundaries along the trace of the Sevier fault in Utah. These boundaries are located, from south to north, near Clay Flat, Alton, and Hillsdale Canyon (figure 2).

### Clay Flat

Anderson and Christenson (1989) identified the 2.5-km-wide en echelon left step in the trace of the Sevier fault at Clay Flat (figures 2 and 6) as a possible seismogenic segment boundary. Black and others (2003) use the Clay Flat step-over as the boundary between the Northern Toroweap and Sevier sections. Seismogenic segments by definition have different surface-faulting chronologies, and determining those chronologies typically requires detailed paleoseismic trenching investigations. No trenching studies have been conducted on either the Northern Toroweap or Sevier sections, but the presence of scarps on unconsolidated Quaternary deposits on the Northern Toroweap section in Arizona, and the absence of scarps north of the en echelon step-over at Clay Flat, argues for a seismogenic segment boundary at Clay Flat.

Furthermore, figure 5 shows an increase in the number

of instrumental earthquake epicenters along the Sevier fault hanging wall from Clay Flat to the south, as compared to the number of earthquakes between Clay Flat and the Alton Gap to the north. We consider this change in seismicity as further evidence that the Sevier fault is segmented at the Clay Flat step over.

### Alton Gap

From Clay Flat north to Black Mountain, a distance of 27 km, the Sevier fault exhibits a complex pattern of closely spaced overstepping fault strands that combine to form at least four relay ramps as slip is transferred between strands (Davis, 1999; Reber and others, 2001; Schiefelbein, 2002). Locally, folds have developed between the overstepping strands, particularly in conjunction with the relay ramps (Schiefelbein, 2002). North from Black Mountain, the trace of the fault is less complex and is commonly mapped as a single strand (Gregory, 1951; Doelling, 1975; Doelling and Davis, 1989; Tilton, 2001). The transition to a less complicated fault structure may have significance for seismogenic segmentation, or it may simply reflect the manner in which the fault is expressed in the softer Cretaceous and Tertiary rocks that crop out in that area as compared to the harder Mesozoic rocks to the south.

In addition to a change in structural style, there is evidence for a significant decrease in slip on the Sevier fault north of Black Mountain. An 8-km-long and as much as 200-m-high obsequent fault-line scarp (figure 4) has developed along the fault southwest and northeast of Alton, where the more resistant Eocene Claron Formation in the hanging wall stands topographically higher than softer Cretaceous rocks in the footwall. Erosional processes typically require considerable time to form an obsequent fault-line scarp, and therefore the scarp near Alton likely represents greatly reduced or no activity on the fault during all or most of Quaternary time. Farther to the northeast, the surface expression of the fault transitions back to a normal, west-facing escarpment despite the continued structural relation of the harder Claron Formation being down-faulted against softer Cretaceous rocks.

A zone of decreased slip or a gap in recent faulting such as that near Alton is characteristic of segment boundaries (Machette and others, 1992; Nelson and Personius, 1993; Chang and Smith, 2002; Nelson and others, 2006). Nelson and Personius (1993) documented a decrease in vertical slip toward both ends of the Weber segment of the Wasatch fault. Chang and Smith (2002) employed a half-ellipse function, with greatest slip near the middle of the segment, to model long-term vertical slip distribution on six central segments of the Wasatch fault that have Holocene surface faulting. Crone and others (1985) showed that vertical slip distribution varied along strike during the 1983 Borah Peak earthquake. Likewise, Chang and Smith (2002) plotted the vertical slip distribution for nine historical Basin and Range earthquakes (including Borah Peak) and showed that slip varied along strike, but typically gradually decreased to zero at the rupture ends. Therefore, evidence for a significant decrease in slip near Alton that is also coincident with a change in structural style is indicative of a possible segment boundary in that area.

Additionally, figure 5 shows that instrumental seismicity (Relu Burlacu, University of Utah Seismograph Stations, written communication, 2007) increases dramatically

in both the footwall and hanging wall of the Sevier fault north of the Alton gap. The increase is particularly evident near Panguitch, where faults in the hanging wall displace Pleistocene alluvial deposits. This increased seismicity is consistent with the relatively high late Pleistocene VSR (0.38–0.44 mm/yr) recorded by displaced Quaternary volcanic rocks at Red Canyon. South of the Alton gap the long-term rate of slip is typically <0.1 mm/yr (table 2), and the number of instrumental epicenters is correspondingly lower.

Relu Burlacu (University of Utah Seismograph Stations, written communication, 2007) used a quality rating system of A (excellent), B (good), C (fair), and D (poor) based on a methodology similar to that used by Arabasz and others (2005) to categorize each of the 664 earthquake epicenter locations shown on figure 5. The quality ratings and number of locations in each category are given in table 3. Fifty-six percent (374) of the locations have a rating of C or better. All A-rated epicenters are on the hanging wall of the Sevier fault near Panguitch. Individual plots of (1) all A and B and (2) of all A, B, and C epicenters showed no significant variation in the distribution of historical earthquakes on either side of the Sevier fault when compared to figure 5, which includes all epicenter locations. We conclude, therefore, that the earthquake locations used for this study are sufficiently accurate to show a real increase in seismicity north of the Alton Gap, and to show the relative distribution of earthquakes in the footwall and hanging wall along the fault.

**Table 3.** *Quality ratings for earthquake epicenter locations along the Sevier fault in Utah.*

Location Quality Rating	Epicenter Location Accuracy	Number of Epicenters
A	± 2 km	19
B	± 5 km	215
C	± 10 km	140
D	> ± 10 km	290

## Hillsdale Canyon

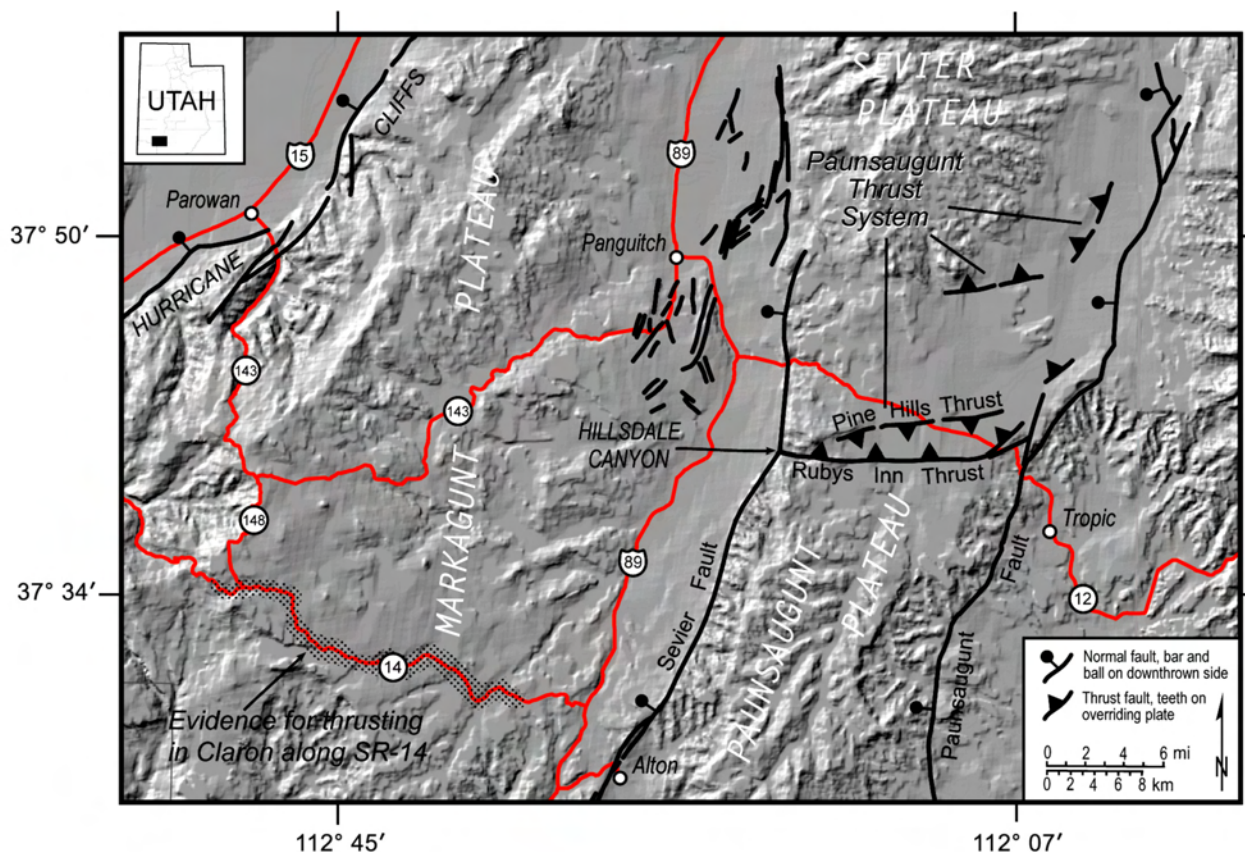
Because the Sevier fault has not been mapped in detail (1:24,000 scale) north of the Kane-Garfield County line (figure 2), fault complexities north of that point may be as yet unrecognized. One complexity that has been recognized even in regional-scale studies (Gregory, 1951; Doelling, 1975) is the intersection of the Sevier fault with the east-striking Paunsaugunt thrust system (Lundin, 1989; Merle and others, 1993; Davis, 1999) near Hillsdale Canyon south of Red Canyon (figure 10). Near Hillsdale Canyon the thrust system consists of the north-dipping Rubys Inn and south-dipping Pine Hills thrust faults (figure 17). The Pine Hills fault is considered to be a back thrust that roots into the Rubys Inn fault (Lundin, 1989; Bowers, 1990). Although Gregory (1951) shows the Pine Hills fault extending to the Sevier fault, Lundin (1989) demonstrated that the fault dies out before reaching the Sevier fault. The Rubys Inn fault can be traced to within 300 m of the Sevier fault, but the intersection is not exposed. However, mesoscale deformation closely associated with the Rubys Inn fault is present in out-

crops that are cut by the Sevier fault (Merle and others, 1993). A prominent change in Sevier fault strike from approximately 030° south of Hillsdale Canyon to 000° north of Hillsdale Canyon can be interpreted to indicate that the Rubys Inn fault may play a role as a segment boundary. However, the thin-skinned style of the Rubys Inn fault makes this scenario unlikely. Cross faults must extend to 12–15 km depth, the typical nucleation depth of larger Basin and Range normal faults, to effectively decouple separate segments of a larger fault (Wheeler and Krystinik, 1992). Lundin (1989) shows the Rubys Inn fault as having a ramp-flat geometry, dipping approximately 30° and soling into the Jurassic Carmel Formation at only about 2 km depth. Additionally, age constraints on the two structures and regional geologic relations argue for the Sevier fault simply cutting and displacing the Rubys Inn fault, rather than there being a structural link and contemporaneous slip between the two structures. The main phase of activity on the Paunsaugunt thrust system occurred between 20 and 30 Ma (Merle and others, 1993; Davis, 1999) whereas the Sevier fault likely initiated sometime between 15 and 12 Ma (Davis, 1999). Although the location of the displaced western continuation of the Rubys Inn fault is unknown, Merle and others (1993) discuss evidence for generally south-directed thrusting to the west in the Markagunt Plateau and suggest that the thrust belt may extend as far as the Hurricane fault (figure 17).

The change in strike of the Sevier fault at Hillsdale Canyon may have resulted from the interaction between the advancing tip of the incipient Sevier fault and the structural and mechanical heterogeneities associated with the Paunsaugunt thrust system, causing a deflection in the trajectory of the propagating fault (G.H. Davis, University of Arizona, written communication, 2006). Or, perhaps linkage of two separate faults with distinct geometries occurred at the latitude of Hillsdale Canyon, similar to linkage models proposed for geometric segments of the Hurricane fault (Taylor and others, 2001; Lund and others, 2002). Regardless of the origin of the bend, slip vectors may not be conserved across such a fault irregularity, creating a nonconservative barrier where ruptures tend to either start or stop (Bruhn and others, 1992; Wheeler and Krystinik, 1992). Criteria for demonstrating the existence of a nonconservative barrier include differences in slip vectors across the barrier, and the development of structural complexities at the barrier such as a third direction of faulting and abrupt changes in displacement between fault segments (Bruhn and others, 1992). Without detailed mapping near the Hillsdale Canyon area, however, the presence of a seismogenic boundary there remains speculative.

## Summary

As presently defined, the 80-km-long Northern Toroweap section and 88-km-long Sevier section, respectively, of the Sevier fault are significantly longer than seismogenic segments recognized on other active Basin and Range faults. These long fault sections are likely divided into shorter seismogenic segments that rupture independently. In addition to the previously recognized possible seismogenic segment boundary at Clay Flat (Anderson and Christenson, 1989; Black and others, 2003), we identify two other possible seismogenic segment boundaries on the SF. Coincident geomet-



**Figure 17.** Relation of the Paunsaugunt thrust system (Rubys Inn and Pine Hills thrust faults) to the Sevier normal-slip fault, Garfield County, Utah (after Davis, 1999).

ric and geomorphic anomalies, differences in stratigraphic displacement, and an abrupt increase in historical seismicity north of the Alton gap indicate the possibility of segment boundaries at Hillsdale Canyon and near Alton. However, until evidence is found demonstrating independent fault histories on each side of the proposed boundaries, they remain conjectural.

## RESULTS

Results of this paleoseismic reconnaissance determined or confirmed the following about the Sevier fault in Utah:

1. Scarps formed on unconsolidated deposits are everywhere absent on the main trace of the fault.
2. Faulting associated with Pearthree's (1998) Northern Toroweap section of the Toroweap fault in Arizona continues uninterrupted across the Arizona-Utah border, and extends for an additional 20 km to Clay Flat.
3. Clay Flat forms a closed topographic and depositional basin that divides the much larger Yellowjacket drainage into upper and lower reaches; the 2.5 km en echelon left step in the trace of the fault at Clay Flat represents a probable seismogenic segment boundary.
4. Major- and trace-element geochemical analyses of the volcanic rock at Black Mountain in the fault footwall show that the rock is a trachybasalt.
5. We, like some previous workers, were unable to determine a well-constrained displacement value for the volcanic rocks at Black Mountain. However, using previously reported displacement values for the volcanics (Cashion, 1961), total displacement across the Sevier fault determined from geologic cross sections (Schiefelbein, 2002), a new average  $^{40}\text{Ar}/^{39}\text{Ar}$  age for the volcanics (Schiefelbein, 2002), and an estimated time of initiation of faulting (Davis, 1999), we calculated late Quaternary and middle Miocene to present VSR and RI estimates of 0.04 mm/yr and 50 kyr, and 0.03-0.07 mm/yr and 40 kyr (range 29-67 kyr), respectively, at Black Mountain.
6. New  $^{40}\text{Ar}/^{39}\text{Ar}$  radiometric ages and major- and trace-element geochemical analyses obtained for volcanic rocks displaced across the fault show that two ages of volcanic rocks are present at Red Canyon: a younger trachyandesite flow with a mean age of  $0.51 \pm 0.02$  Ma north of SR-12, and an older trachybasalt flow with a mean age of  $4.96 \pm 0.03$  Ma south of SR-12. Each of the two flows is also chemically correlative across the fault.



7. Our field reconnaissance at Red Canyon identified a cinder cone or cluster of smaller spatter cones on the hanging wall of the fault north of SR-12, which provides a source for the younger displaced flow. The reconnaissance also showed that the distinctive white sedimentary unit directly beneath the remnant of the young flow in the fault footwall north of SR-12 is not the "white Claron" subunit of the Claron Formation, but is likely an erosional remnant of the conglomerate at Boat Mesa from lower in the Claron section. A second white sedimentary unit on the fault hanging wall at the base of the bedrock escarpment directly below the white unit in the footwall contains flecks of biotite and is likely related to the Mount Dutton volcanics. Thus the vertical separation between the two white units cannot be used to measure displacement across the fault at Red Canyon.
8. Our literature review identified a mafic volcanic flow on the west side of the Sevier River along U.S. Hwy 89 about 5 km north of Hatch that was dated at 5.3 Ma. The source of this older flow is likely farther west on the Markagunt Plateau and indicates that the older volcanic flow at Red Canyon may also have its source to the west.
9. Using the new  $^{40}\text{Ar}/^{39}\text{Ar}$  radiometric ages and estimates of the displacement of the two volcanic flows across the fault, we calculated late Pleistocene and early Pliocene to present VSR and RI estimates of 0.38-0.44 mm/yr and 4.4-5.3 kyr, and 0.05-0.07 mm/yr and 29-40 kyr, respectively, at Red Canyon.
10. An estimated 900 m of displacement across the fault in basement rock at Red Canyon determined from seismic reflection data, and an estimate of the time of initiation of faulting of 12-15 Ma, allowed us to calculate middle Miocene to present VSR and RI estimates for the fault at Red Canyon of 0.06-0.08 mm/yr and 25-33 kyr, respectively.
11. Scarps formed on middle to late Pleistocene alluvium in the hanging wall of the fault near Panguitch are likely tectonic in origin and could be trenched, but in the absence of trench sites on the main trace of the Sevier fault for comparison, the relation of paleoseismic information determined from the hanging-wall scarps to the main fault would remain unknown.
12. The long lengths of the Northern Toroweap (80 km) and Sevier (88 km) segments are anomalous when compared to the length of seismogenic segments on other active faults in the Basin and Range Province. In addition to a probable seismogenic segment boundary at Clay Flat identified by Anderson and Chris-

tenson (1989), we identify two other possible seismogenic boundaries in Utah near Alton and at Hillsdale Canyon.

## CONCLUSIONS

Based on the results of this paleoseismic reconnaissance, we conclude that with the exception of the northern Sevier fault near Panguitch, the current VSR along the Sevier fault in Utah is  $< 0.1$  mm/yr and the RI between surface-faulting earthquakes is  $\geq \sim 30$  kyr. At the north end of the fault, well-documented geologic relations at Red Canyon show that the late Pleistocene VSR is 0.38-0.44 mm/yr, and the RI for surface faulting is estimated at 4.4-5.3 kyr. A more active northern part of the fault is further supported by the presence of numerous geologically young faults and folds formed in middle to late Pleistocene alluvial deposits in the fault hanging wall near Panguitch, as well as by a significantly greater level of historical seismicity north of the Alton gap. It is unknown if the hanging-wall scarps are related to coseismic surface faulting or to folding, but their presence, along with the folds, indicates that tectonic deformation is ongoing in the Sevier fault hanging wall near Panguitch.

A pronounced en echelon left step in the trace of the Sevier fault at Clay Flat along with the presence of a closed basin that divides the much larger Yellowjacket drainage into unconnected upper and lower reaches, provides evidence of a probable seismogenic segment boundary between the Northern Toroweap section to the south and the Sevier section to the north. It is 88-km from Clay Flat to the terminus of the Sevier fault northeast of Panguitch, a distance that exceeds the length of recognized seismogenic segments on other active faults in the Basin and Range Province. The long length presently projected for the Sevier segment, and clear evidence for enhanced fault activity at the north end of the fault, argue for an additional segment boundary(s) somewhere between Clay Flat and the northern fault terminus. Geomorphic and geometric relations show that possible segment boundaries may be present near Alton, where an obsequent fault-line scarp has formed along the fault, and near Hillsdale Canyon, where the fault intersects and appears to displace the older Paunsaugunt thrust system.

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## APPENDIX A

### Geochemical Analyses of Mafic Volcanic Rocks Displaced by the Sevier Fault at Black Mountain, Kane County, and Red Canyon, Garfield County, Utah analyzed by Washington State University GeoAnalytical Laboratory Pullman, Washington

Element	SF-1 <sup>1</sup> Red Canyon	SF-3 <sup>1</sup> Red Canyon	SF-5 <sup>2</sup> Red Canyon	SF-8 <sup>2</sup> Red Canyon	SF-10 <sup>3</sup> Black Mountain
<b>Unnormalized Major Elements (Weight %)</b>					
SiO <sub>2</sub>	59.14	59.21	50.13	49.82	49.45
TiO <sub>2</sub>	1.074	1.080	1.397	1.401	1.822
Al <sub>2</sub> O <sub>3</sub>	15.51	15.57	15.44	15.34	16.36
FeO	6.26	6.31	8.66	8.66	8.88
MnO	0.102	0.103	0.146	0.148	0.146
MgO	4.47	4.38	7.87	8.02	7.81
CaO	5.54	5.32	9.31	9.32	8.14
Na <sub>2</sub> O	4.30	4.32	3.08	3.15	3.97
K <sub>2</sub> O	2.11	2.14	2.13	2.12	1.73
P <sub>2</sub> O <sub>5</sub>	0.440	0.441	0.562	0.565	0.677
Total	98.94	98.89	98.73	98.53	98.98
<b>Normalized Major Elements (Weight %)<sup>4</sup></b>					
SiO <sub>2</sub>	59.77	59.88	50.77	50.56	49.96
TiO <sub>2</sub>	1.085	1.092	1.415	1.422	1.841
Al <sub>2</sub> O <sub>3</sub>	15.67	15.75	15.64	15.57	16.53
FeO	6.33	6.38	8.78	8.78	8.97
MnO	0.103	0.104	0.148	0.151	0.148
MgO	4.52	4.43	7.97	8.14	7.89
CaO	5.60	5.38	9.43	9.46	8.23
Na <sub>2</sub> O	4.35	4.37	3.12	3.19	4.01
K <sub>2</sub> O	2.13	2.17	2.15	2.16	1.74
P <sub>2</sub> O <sub>5</sub>	0.445	0.446	0.569	0.573	0.684
Total	100.00	100.00	100.00	100.00	100.00
<b>Unnormalized Trace Elements (ppm)</b>					
Ni	108	107	150	153	153
Cr	137	134	308	307	228
Sc	14	14	27	28	23
V	108	106	207	211	161
Ba	1678	1660	1520	1511	823
Rb	29	30	48	48	14
Sr	1109	1087	1025	1028	1009
Zr	229	233	170	170	236
Y	20	21	24	24	26
Nb	20.8	20.2	20.4	20.2	19.8
Ga	18	19	17	18	15
Cu	28	26	39	43	41
Zn	85	86	82	81	77
Pb	18	17	9	8	8
La	59	62	59	60	44
Ce	119	117	120	108	93
Th	6	4	6	5	4
Nd	49	49	56	54	46

<sup>1</sup>Samples SF-1 and SF-3 are from the footwall and hanging wall, respectively, of the Sevier fault north of SR-12; their locations correspond to the locations of radiometric age samples SF-2 and SF-6 (see table 1).

<sup>2</sup>Samples SF-5 and SF-8 are from the footwall and hanging wall, respectively, of the Sevier fault south of SR-12; their locations correspond to the locations of radiometric age samples SF-4 and SF-7 (see table 1).

<sup>3</sup>Sample SF-10 is from the footwall of the Sevier fault at Black Mountain (UTM 12 S 0364008, 4138450).

<sup>4</sup>Major elements are normalized on a volatile-free basis, with total Fe expressed as FeO.



## APPENDIX B

### Variation Diagrams for Volcanic Rocks at Black Mountain, Kane County, and Red Canyon, Garfield County, Utah (Diagrams prepared by R.F. Biek, UGS, 2007 using IgPet software by Terra Soft Inc.)

Note: Young Red Canyon volcanic rocks are samples SF-1 and SF-3. Old Red Canyon volcanic rocks are samples SF-5 and SF-8. Black Mountain volcanic rocks are represented by sample SF-10. Variation diagrams for Ba vs. Cr, Nb vs. Nd, Sr vs. Rb, and Sr vs. Zr are calibrated in parts per million, plots of  $\text{Na}_2\text{O}+\text{K}_2\text{O}$  vs.  $\text{SiO}_2$ , and  $\text{TiO}_2$  vs.  $\text{P}_2\text{O}_5$  are calibrated in weight percent. See appendix A for complete geochemical analyses.

